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TITLE PAGE

UNIVERSITI TEKNOLOGI PETRONAS

Sedimentological Study of Batu Gading Limestone, Long Lama, Sarawak

By

Muhammad Rahmani bin Hamzah

A THESIS

SUBMITTED TO THE POSTGRADUATE STUDIES PROGRAMME

AS A REQUIREMENT FOR THE

DEGREE OF MSC. PETROLEUM GEOSCIENCES

PETROLEUM GEOSCIENCES

BANDAR SERI ISKANDAR,

PERAK.

DECEMBER, 2007

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has been previously or currently submitted for any other degree at UTP or other institutions.

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ABSTRACT

The study was conducted at three different localities in Batu Gading area near a small town of Long Lama in 4th Division, Sarawak. The area is located at the latitude of 3° 45' to 3° 50' N and the longitude of 114° 30' E. The Batu Gading limestone is considered as part from the Nummulitic Limestone and the Melinau Limestone which were previously dated as Late Eocene and Early Miocene, respectively. The Nummulitic Limestone has a total thickness of 28m and is conformably underlain by the highly folded turbidite clastic sequence of the Kelalan Formation (?Late Cretaceous) and overlain by 50m of the Fossilifereous Limestone (Early Miocene). This limestone is disconformably overlain by clastic sequence of Setap Shale equivalent.

The Batu Gading limestone shows several transgressive (TST) and high system tracts (HST) as implied from the sedimentary sequences. Several sequence boundaries were also identified within the sequences. The major SBs were recognized at the boundaries between the Kelalan Formation (Late Cretaceous) and the Nummulitic Limestone (Early Miocene) and also between the Nummulitic Limestone (Late Eocene) and Fossilifereous Limestone (Early Miocene). Disconformity surface was also observed at the boundary between the Fossilifereous Limestone and the overlying clastic sequence of the Setap Shale equivalent. Another SB was recognized at the second locality that separates the HST and TST.

Two major limestones were observed namely the Nummulitic Limestone (Late Eocene) and Fossilifereous Limestone (Early Miocene). The Fossilifereous limestone could be further subdivided into breacciated limestone, lepidocyclina limestone, and other fossilifereous limestone. Generally, three types of limestone were recognized based on Dunham's classification; grainstone, packstone and wackestone. The limestones are generally dark grey to white, massive, well bedded, dense, and contain abundance of larger foraminifera and other fauna. They generally contain high percentage of allochems and micrite and show very low porosity and permeability.

The Nummulitic Limestone (Late Eocene) sequences have been interpreted to be deposited as bank deposits. The inter-bedded between the Nummulitic Limestone

and muddy limestone suggests that they were deposited within the bank areas and extended further to outer part of basin. The Fossilifereous Limestone (Early Miocene) were deposited as reef core, slope and basinal as suggested by the presence of massive coral heads (reef core), massive, platty, and branching corals (slope deposits) and brecciated limestone (distal slope to basinal areas). The second and third localities are located more distal as compared to the first locality. The presence of abundant planktonic foraminifers suggests that the environment should be at the deeper area in the basinal areas.

Diagenesis has affected the limestone quite significantly. As a result, the porosity is relatively very low due to extensive compaction and calcite and dolomite cementation. Fibrous cement indicates a marine water diagenesis while the presence of equant calcite suggests precipitation within a fresh water environment.

The Nummulitic Limestone as bank deposits is considered the best reservoir for exploration. The inter-bedded Nummulitic Limestone and muddy limestone provides a good basis for subdivisions of the massive Nummulitic beds to be used in reservoir geological modeling.

ACKNOWLEDGEMENTS

In the name of Allah, The Most Gracious and The Most Merciful

Thank goodness to the God as the strength and opportunity has been bestowed on me in completing this industrial project within the provided time. I would like to grant my gratitude especially to beloved parents, En Hamzah bin Hj. A. Rahman and Pn, Fadlon bte Hj. Mohamad, the adored members Intan Hasfaezah, Fauzi, Idayu Farahaida, Halim, Iskandar Nazarullah, Hidayah, Nurul Ann Nadia, Nur Amalina and Azahaina for the supports given. Also soaring appreciations especially to the supervisor, En Mohamad Yamin bin Ali with co-supervisor, Pn. Asiah bte Mohd Salleh for guiding and monitoring this project. Not forget to Mohamad Faizal bin Idris, all classmates, for those who gave the helps, verve and the ideas to accomplish this study. Without all of you, this thesis will not be existed. Thank you so much.

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CHAPTER ONE : INTRODUCTION

1.1 Problem statement

Two general stratigraphic studies were carried out in the Batu Gading area (Adams and Haak, 1962; Haile, 1965) based on limited sedimentary sequences that were exposed along the Baram River between the Long Lama and Batu Gading towns. However, no detailed sedimentological models and depositional environment interpretations have been established to represent two major carbonate sequences; the Nummulitic Limestone of Late Eocene and the Foraminiferal Limestone of Early Miocene. Furthermore, the potential of the Nummulitic Limestone as a good reservoir analogue similar to the one found in Libya and Tunisia, and the Miocene carbonate similar to the one found in the Central Luconia have never been evaluated.

1.2 Objectives

The objectives of the study were to develop depositional and sedimentological models and to establish sequence stratigraphic framework of the Batu Gading Limestone that consists of the Nummulitic limestone (Late Eocene) and Foraminiferal Limestone (Early Miocene) sequences to be used as exploration and development models for similar types of carbonate.

1.3 Tectonic Evolution of Sarawak

The Sarawak evolution was initially interpreted using a geosynclinal theory of Haile (1969). Deepwater turbidite rocks in Sibu zone were interpreted as eugeosynclinal where as the coastal-neritic sediments in the Miri zone acts as miogeosynclinal (Haile, 1969). The pre-Tertiary tectonic development of Sarawak can be traced during break-up of the Gondwanaland and the evolution of palaeo-Tethys whereas the western Borneo Basement is part of Sundaland craton (Hutchison, 1989). During the Late Carboniferous to Early Permian, shallow marine sedimentation took place as seen in the Terbat Formation when the West Borneo basement was still attached to Gondwanaland. Sedimentation was later interrupted by a major tectonic event during the Middle Permian to Early Triassic, followed by sedimentation of continental to shallow marine sediments of the Sadong Formation. Widespread basaltic are evidenced by Upper Triassic Serian Volcanics, while elsewhere marine sedimentation continued into the Jurassic and Cretaceous that associated with basic volcanism of the Pedawan Formation. During the Early-Middle Cretaceous, deposition was locally interrupted by folding that affected the Pedawan Formation and igneous activity during the Late Cretacaeous. Towards the east of Lupar area, marine turbidite of Belaga Formation was deposited in the basin until Late Eocene and it was probably associated with a subduction zone of Lupar Line. Same sequence has been found in Kelalan Formation near Batu Gading area, indicating a widespread sedimentation across Sarawak. In Late Cretaceous, western Sarawak was already uplifted and the Kayan Sandstone of continental deposits were deposited into the Miocene with the deposition if the Silantek Formation.

The Sarawak evolution of the Late Mesozoic to Early Cenozoic is controlled by subduction and collision processes at the northern margin of western Borneo. The Kuching and Sibu zones are interpreted as Mesozoic-Early Cenozoic accreted crustal material as the Rajang Sea was subducted southwestwards beneath west Borneo. The Miri zone represents the onshore extension of the Sarawak Basin that developed during the Late Eocene on the uplifted continental margin formed by the Kuching and Sibu zones. Since the Middle Cretaceous, the West Borneo Basement became a part from Sundaland. A counter-clockwise rotation of Borneo occurred during the Cretaceous and Cenozoic.

The Sarawak continental shelf represents the sedimentary succession that exceeds 12 km of siliciclastic sediments derived from the erosion of the uplifted Rajang Fold- Thrust Belt. Sarawak Basin was defined as the upper Eocene-Recent age. The lower part of the Sarawak Basin crops out as the onshore Miri zone while the remainder lies mostly in the continental shelf and slope of Sarawak. The Sarawak Basin is subdivided into several tectono-stratigraphic provinces based on structural styles and sedimentation histories. Tinjar and Tatau provinces are tectonic provinces that are extended further onshore.

The Sarawak Basin has originated as a foreland basin that formed after the collision of the Luconia block with the west Borneo basement. Deformation of the Rajang Group accretionary prism later formed the Sibu zone and provided the sediment supply to the Sarawak Basin. The Sarawak Basin originated as a foreland depression basin during the Oligocene to Early Miocene and later subjected to active extensional and strike-slip tectonics, but later underwent coastal-shelf progradation and passive continental margin outbuilding during the Middle Miocene to Recent. However, some authors have interpreted the Sarawak Basin as a strike-slip basin based on structural styles and subsidence history (Mazlan et al, 1999).

1.4 Regional Setting of Sarawak

Generally, Sarawak state is located in the island of Borneo at the latitude of 0° 50' to 5° N and longitude 109°36' to 115° 40' E, extending some 800 km along north-west coast. It is bounded to the west by the South China Sea, to the north by Sabah state, and to the east and south by Kalimantan (Fig.1.1).

Geologically, Sarawak could be separated into three major structural zones which are known as Kuching, Sibu and Miri Zones (Fig. 1.2). The sedimentary deposition in Sarawak is generally younging from west to east and from south to north (Mazlan, 1999). The oldest rock is represented by Pre-Tertiary west Borneo Basement (Fig.1.2) that is exposed in the southern and extending southward into Kalimantan. This zone is believed to be continental core of Borneo and assumed to be the eastward extension of Sundaland (Hutchison, 1989). The Kuching zone is believed to be the peripheral part of continental basement of West Borneo Basement (Mazlan, 1999). This zone contains the oldest rock of Kerait Schist and Tuang Formation (pre-Late Carboniferous) with Carbo-Permian and Upper Triassic limestone, which are overlain by mixed terrestrial / marine deposits sequence (Upper Triassic). The sequence continuously deposited as several formations of marine siliciclastic deposits with small part of carbonates occurrence (Jurassic to Cretaceous). During Upper Cretaceous to Middle Miocene, the zone was covered by mixed terrestrial / marine and minor non-marine siliciclastic deposits.

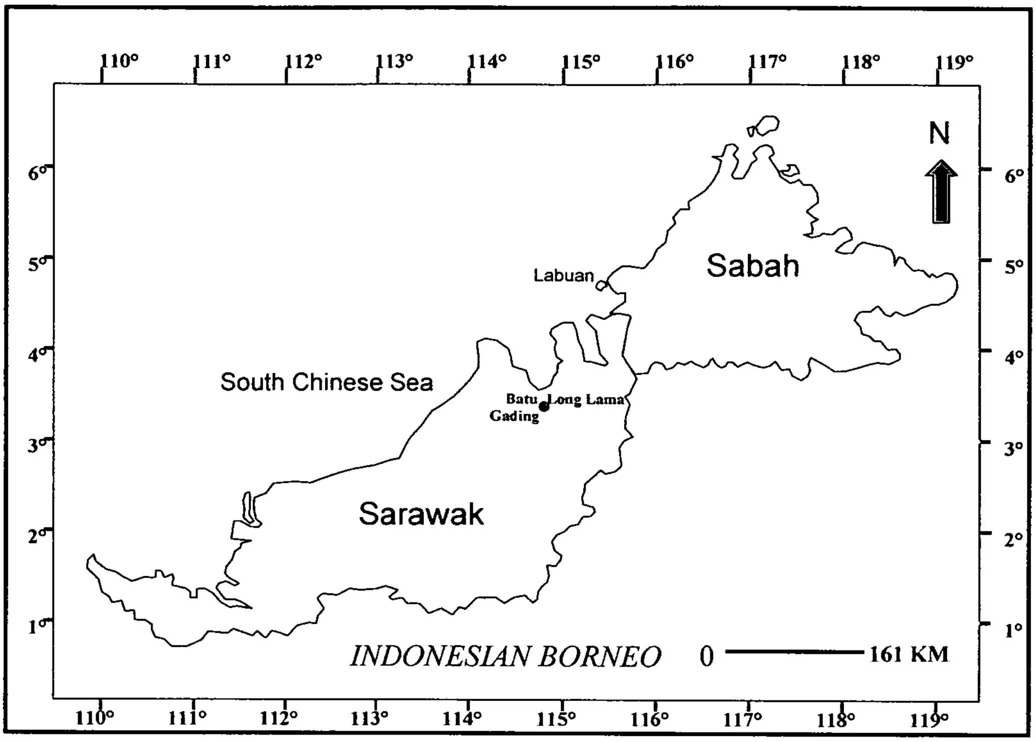

Figure 1.1: The location of Sarawak and Sabah, Malaysia

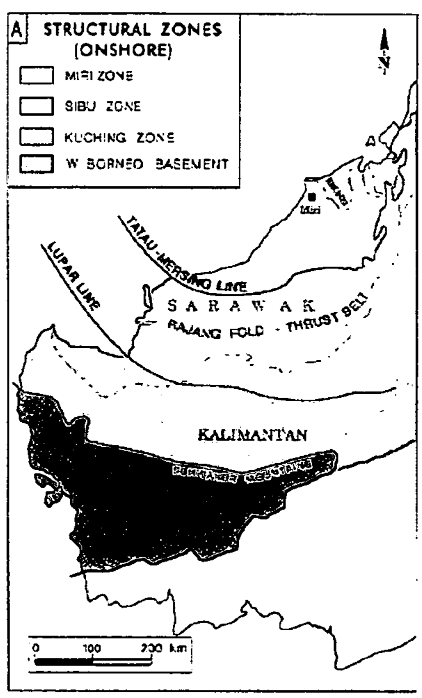

Figure 1.2: The Sarawak Zones (after Leitchi et al.; 1960, from Mazlan, 1999)

The Kuching Zone is separated from Sibu Zone at the eastern boundary by the Lupar line, a NW-trending zone of mélange (Lubok Antu Melange). The Lubok Antu Melange comprises of blocks of sandstone, radiolarian chert, basic igneous rocks, and limestone in sheared mud matrix, and believed to be the tectonic mélange which was formed during Eocene (Tan, 1982 and Haile et al., 1994). Basically, this zone consists of two formations namely the Lupar Formation (Cretaceous) that was overlain by the Belaga Formation (Cretaceous to Eocene). These two formations are incorporated into Rajang Group as well as Danau Formation and Embaluh Group in adjacent Kalimantan (Hutchison, 1996). This zone is believed to be formed due to the deformation and uplift of the Rajang Group accretionary prism to form the Rajang Fold-Thrust Belt. The zone supplied the sediments clastic for the Sarawak Basin.

The Sibu Zone is separated from the Miri Zone by the Tatau- Mersing Line. The Miri Zone is assumed as the youngest sediments deposited in the Sarawak region. The Tatau-Mersing Line shows a major unconformity between Belaga, Mulu, and Kelalan Formation, with overlying Upper Eocene- Recent sediments of this zone (Mazlan, 1999). The unconformity is happen in the Late Eocene in Sarawak, which is believed to be associated with the Central Luconia plate collision. Another prominent hiatus occurred during the Late Eocene which impacted the the Melinau Limestone as one could see in the Batu Gading Limestone sequence. This unconformity shows the major tectonic phase that deformed the deep marine rocks of the Rajang Fold-Thrust Belt. The oldest formations that have been documented are the Mulu and Kelalan Formations, deposited respectively during the Cretaceous and continuously until the Upper Pliocene. Most of these Formations in this Miri zone are from marine siliciclastics and mixed terrestrial / marine deposits, except for the Melinau Limestone Formation. This limestone was formed as an isolated limestone but quite different from the carbonates in offshore Sarawak.

The Batu Gading Limestone that consists of the Late Eocene of Nummulitic Limestone and the Early Miocene of Melinau Limestone equivalent would be studied in greater details in this particular project.

1.5 The Batu Gading Limestone

The carbonate development in the Batu Gading area took place as early as Late Eocene as shown by the presence of Nummulitic Limestone that unconformably overlain the highly folded of the Kelalan Formation. The Batu Gading Limestone is made up of the Nummulitic Limestone and part of the Melinau Limestone (Fig. 1.3). This Melinau Limestone is dated as Early Miocene and subsequently overlain by the Setap Shale. The stratigraphical column as shown in Figure 1.4 shows the regional relationship between the Melinau Limestone and other Formations in the Miri area.

The Batu Gading area which is recently studied is located in the Middle Baram region between the latitude of 3° 45' to 3° 50' N and longitude of 114° 30' E. The outcrops are exposed in several localities within 5 km distance between Batu Gading and Long Lama towns. However, three outcrop localities were chosen for this study.

Generally, the Nummulitic Limestone sequence is rather massive, very hard, dense, and medium-grey in color with more sandy at the base. The outcrops exposed at the Long Lama and Batu Gading quarries show continuous beds with more or less equal thicknesses. Although, a total of 30- 45 meters high and discontinuous of 1.5 km width of limestones are exposed, the Nummulitic limestone is found to be more massive in certain locality and more bedded in other localities. Similarly, the Melinau Limestone equivalent shows some differences from one locality to another. This limestone contains various types of fossils mainly foraminifera, coral, brachiopods and occasionally mollusks. At one locality, this limestone consists of more brecciated limestone, indicating the deposition at the base of slope. In comparison to other localities, more in-situ massive and branching corals are present, indicating deposition near the reef core or at the proximal part of the slope.

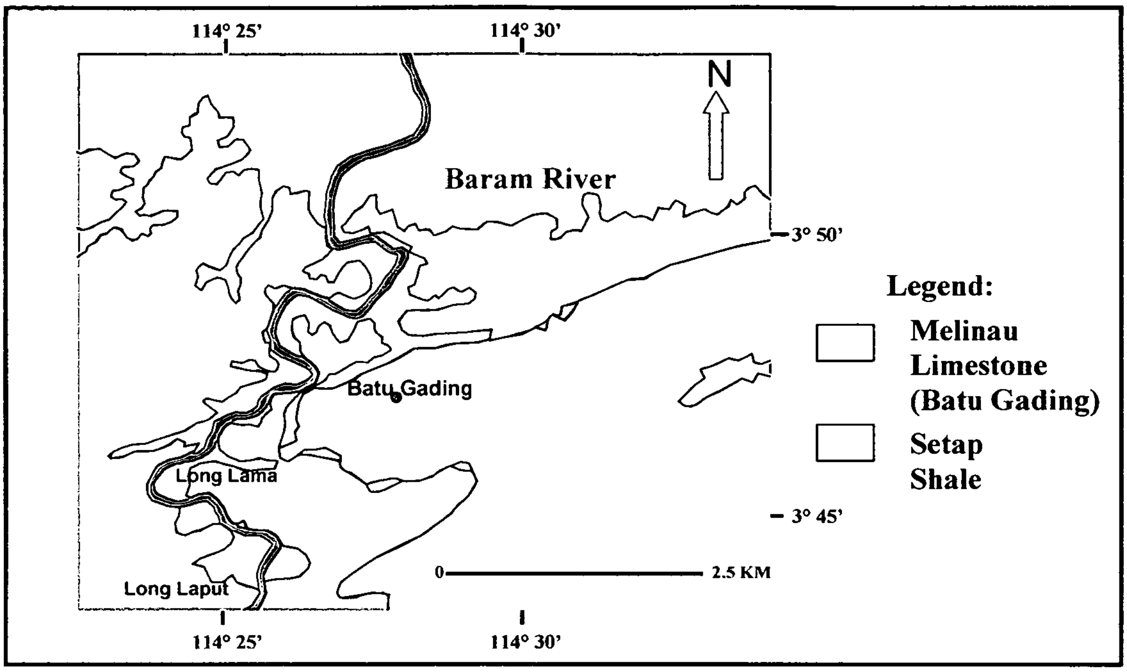

Figure 1.3: The geological map shows the study area at the Batu Gading area. The area has been conformably covered by the Nummulitic (Late Eocene) and Melinau Limestones equivalent (Early Miocene), and finally overlain by the Setap Shale

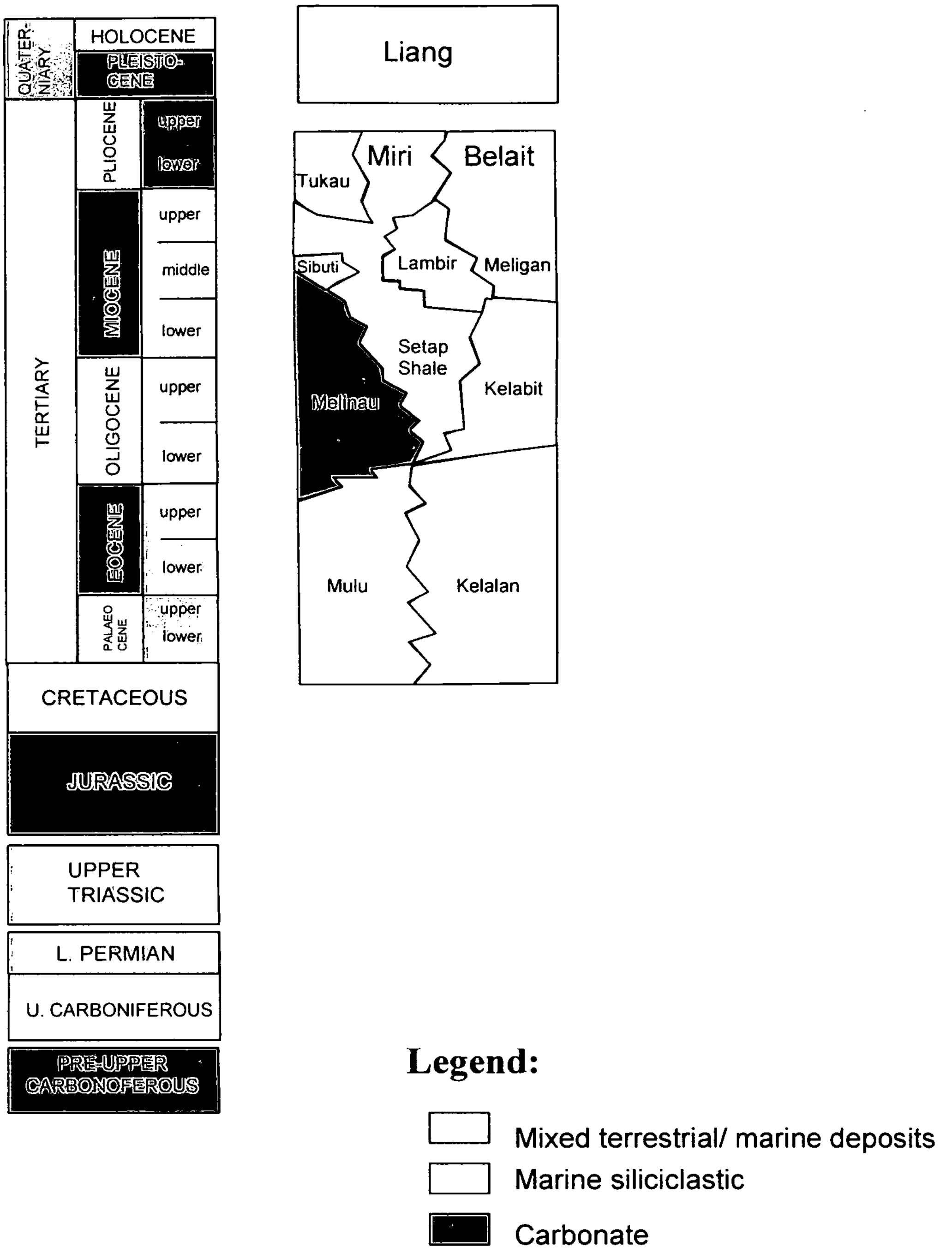

Figure 1.4: Stratigraphic chart showing the relationship between the Melinau Limestone and other Formations in the Miri area, modified after Geological Survey of Malaysia (1995) in Mazlan (1999)

1.6 Stratigraphy of the Batu Gading Limestone

Based on Haile (1962), several typical Eocene larger foraminifera were identified from the Batu Gading area. Among others are *Nummulites* cf. *saipanensis* Cole, *Pettalispira* cf. *provaleae* Yabe, *Halkyardia bikiniensis* Cole, *Eorupertia plecte* (Chapman), *Discocyclina ompala* (Fritsch), *Lepidocyclina* (Nephrolepidina) sp., *Spiroclypeus* sp., *Austrotrillina* howchini and *Borelis* pygmaeus (Haile, 1962; Adams and Haak, 1965). *Globigerina dissimilis*, *Globigerina binaiensis*, *Globigerinoides* spp, *Globorotalia mayeri*, and *Globoquadrina venezuelana* (Haile, 1962) species were used to mark the boundary between Early-Late Miocene. The presence of *Heterostegina* spp., *Lepidocyclina* spp., *Miogysinoides* spp., *Operculina* spp. and *Neoalveolina pygmae* (Haile, 1962) were used as a basis for the Miocene age determination.

Generally, the Nummulitic Limestone was dated as Late Eocene while the Melinau Limestone equivalent section was dated as the Early Miocene. The Nummulitic Limestone was interpreted to be deposited as bank deposits. The Early Miocene carbonates were interpreted to be deposited in reef core to outer- basinal environments.

1.7 Scopes and Methods

Figure 1.5 shows a step-by-step work flow on how the project was conducted within a given 4-month period. The project started by conducting a literature review to understand the regional geology and carbonate depositional systems. It was followed by preparing and conducting a 7-day fieldwork. During the fieldwork, the field observation was done by logging of sedimentary sequences and features together with fossils identification, collecting field evidences by taking photographs, and collecting samples for thin section preparation and petrographic analysis. Furthermore, the limestone beds (strike and dip), types of surfaces and contacts, and the fossils content systematically recorded to help preparing the analysis, interpretation, and report writing.

The collected samples were studied using thin sections that were prepared in the laboratory. Petrography analysis was done to identify fossils content for microfacies determination, and diagenesis. This microscopic study is useful for rock naming and interpretation of depositional environments and age dating.

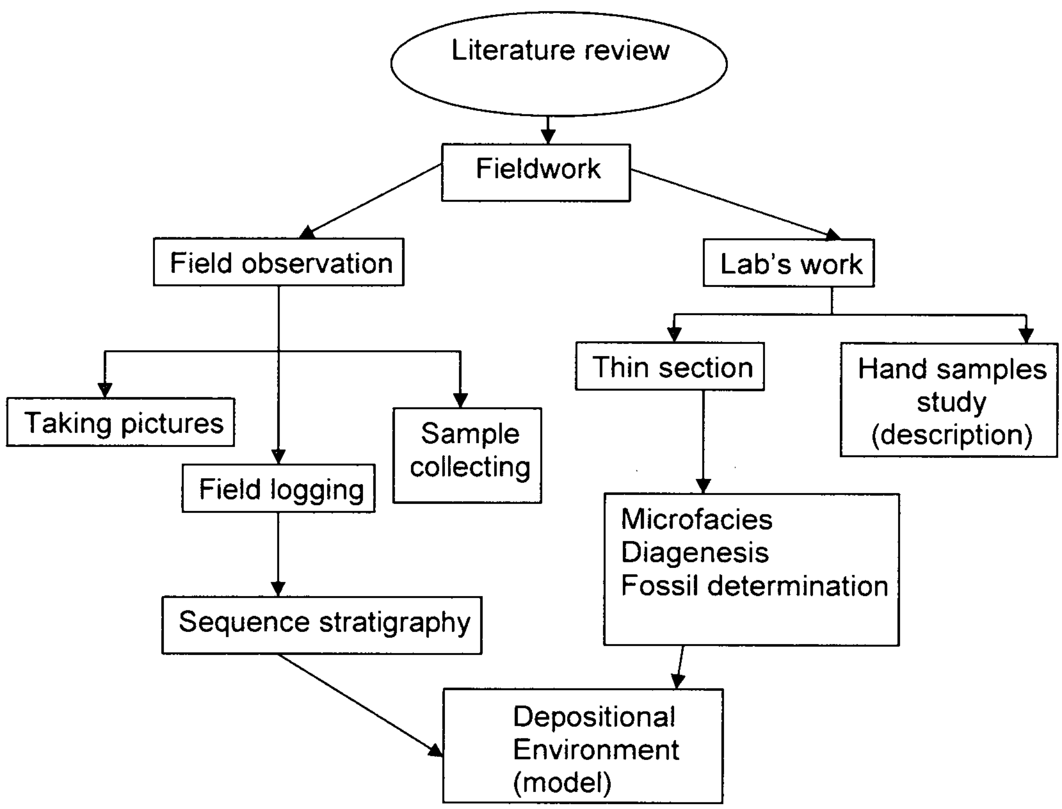

Figure 1.5: The simplified chart showing step-by-step work flow in carrying out the project

CHAPTER 2 : LITERATURE REVIEW

2.1 Literature Review

The Batu Gading limestone was studied earlier by N.S. Haile (1956), R. Haak (1958), Lietchi *et al.* (1960), F.H. Fitch (1961), Haile (1962), Adam and Haak (1962), Adam (1965). According to Fitch (1961), this limestone is considered as part of the Melinau Limestone Formation, similar to Keramit, Selidong, and Tujuh- Siman Limestones. Adam and Haak (1962) reported that the Batu Gading Limestone is made up of predominantly Late Eocene (Nummulitic Limestone) and separated by a disconformity. Leitchi *et al.* (1960) also reported that the Batu Gading Limestone forms as lens and found to be exposed at about 3 miles from Long Lama town. The lower part of the Batu Gading Limestone consists of hard, medium-grey massive limestone with well preserved foraminifera, corals, brachipods, and occasionally mollusks in an organic groundmass. Similar observation was also made by Haile (1962).

The contact between Melinau Limestone Formation and the underlying Kelalan Formation is very well exposed in the Batu Gading area (Adams and Haak, 1962). According to Haile (1962), there are indications of an unconformity contact between the Melinau Limestone and the Kelalan Formation (Cretaceous) based on the outcrops exposed at Bukit Bersungai (northeast). He considered that the underlying beds at Batu Gading belonged to the Kelalan Formation which was dated as Early Eocene or Late Cretaceous. Adam (1965) recorded that the Nummulitic Limestone at Batu Gading unconformably overlying the late Cretaceous turbiditic sandstones and shales. In fact, the relationship between Melinau and Kelalan Formations is not clear until the discovery of diverse Cretaceous fauna by Adam and Haak (1962). At the Lower Temala River, the Melinau Limestone Formation apparently rests almost directly on steeply dipping alternating sandstone and shale, but the actual contact has not been seen and assumed to be folded harmonically instead of unconformity (Haile 1962). In the middle Temala valley, the sandstone of Temala Member conformably underlies the limestone.

The Batu Gading succession is made up of the Late Eocene (Tb) to Early Miocene (Te $_{1-4}$) (Haile, 1962; Adam and Haak, 1962; Adam, 1965; Lee *et al.* 2004). The Eocene thickness is about 210 feet while the Miocene represents approximately 160 feet section (Adam & Haak, 1962; Adam, 1965). The Late Eocene succession is made up of dark grey massive limestone, very hard, dense, and slightly sandy towards the base (Haile, 1962; Adam and Haak, 1962; and Lee *et al.* 2004). Adam (1965) reported that the Eocene section of the Batu Gading Limestone is consisted of abundant larger Foraminifera and calcareous algae. The limestone bedding is dipping about 12-15 degree to northward and the larger foraminifera become the major constituents of the Batu Gading Limestone (Adam and Haak, 1962).

Leitchi (1960) has documented some typical foraminifera that are present in the Eocene part of the Batu Gading area such as *Aktinocyclina* sp., *Nummulites* cf. *globules* Leymerie, *Pellatispira madaraszi* Hantken and *Pellatispira crassicolumnata* Umbgrove. Adam and Haak (1962) also mentioned the occurrence of algae, corals (fragments), with bryozoan debris, echinoid and larger foraminifera. *Pellatispira* spp., *Nummulites* sp., *Nummulites* cf. semiglobulus, *Discocyclina* spp., *Aktinocyclina* sp. and also the calcareous algae like *Melobesieae* and *Archaeolithothamnium* sp. About 25 feet of limestone breccia and bedded limestone with a thickness of 15 feet were observed (Haile, 1962; Adam and Haak, 1962; and Adam 1965). The Late Eocene-Early Miocene boundary is not often lithologically distinct; however there is a clear-cut lithological boundary visible when the Eocene limestone is overlain by calcareous silty shales (Adam and Haak, 1962). The limestone breccia, containing Eocene large blocks with a great quantity of branching and massive corals, as well as reworked Eocene foraminifera of *Te* age are also found, (Adam and Haak, 1962 and Adam, 1965). These include *Austrotrillina howchini, Heterostegina* sp., *Miogypsinoides* sp., *Nephrolepidina* sp. and *Spiroclypeus* cf. *tidoenganensis*.

The sequence changes into bedded limestone that comprises of alternating fine, medium and coarse grained bioclastic, algal-foraminiferal calcarenites, hard, light grey dense and becomes more sandy toward the top (Adam and Haak, 1962). Algal, echinoidal debris, fragmental bryozoans, mollusks and abundantly benthonic and pelagic foraminifera are the major constituents of this bed. The identified foraminifera are *Heterostegina* spp., *Lepidocyclina* spp., *Miogysinoides* sp., *Operculina* spp. and *Neoalveolina pygmaea* (Hanzawa) (Adam and Haak, 1962).

This well bedded limestone is conformably overlain by calcareous shale which is believed to be part of Setap Shale Formation (Lee *et al.* 2004). With an average thickness of about 7 inches, this bed often alternates with calcareous sandstones and sandy limestone and acts as a transitional sequence into a major shaly sequence at the top (Adam and Haak, 1962). The bed is becoming slightly more sandy at the base and rich in pelagic foraminifera such as *Globigerina binaiensis* Koch, *Globigerina* cf. *ciperoensis* Bolli, *Globigerina dissimilis* Cushman & Bermudez var., *Globigerina* spp., *Globigerinoides quadrilobatus trilobus* (Reuss), *Globoquadrina venezuelana* (Hedberg) var. and *Globorotalia* cf. *mayeri* Cushman & Ellison (Adam, 1965).

In term of the depositional environment setting, Fitch (1961) proposed that the Melinau Limestone was interpreted to be deposited in shallow marine conditions (75-100 feet). The Batu Gading Limestone was interpreted to be developed in reef environment (Leitchi, 1960). Based on fossils content, Adam 1965 has concluded that the Eocene part of the Batu Gading Limestone was interpreted as shoal facies.

CHAPTER 3 : RESULTS

3.1 Introduction

Three outcrops located at Hollystone Quarry sites in Batu Gading-Long Lama were studied for this purpose. The outcrops are located at N 03° 47.848' and E 114° 26.675' based on GPS readings. These outcrops display a complete limestone and clastic sequence. However, this study only focuses in describing and interpreting the limestone section. The Dunham classification (1962) and Embry & Kloven (1971) were used in this study. More detailed facies description was done based on petrographic observation.

3.2 Dunham Classification

This classification was established by Dunham (1962) based on percentages of allochem and matrix and depositional rock fabric. Under this scheme, 6 types of limestone namely mudstone, wackestone, packstone, grainstone, boundstone and crystalline are classified. Based on field observation, most limestones were classified as packstone-grainstone. The detailed description is given the Figure 3.1.

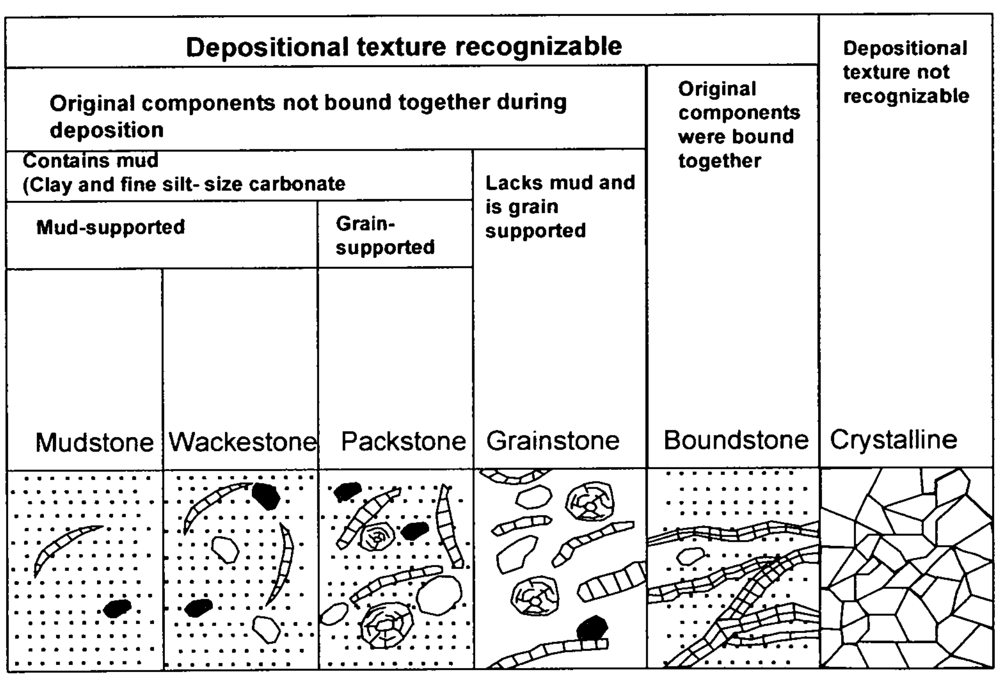

Figure 3.1: The Dunham classification (1962), modified after AAPG 77

3.3 Locality 1 Outcrop

Based on GPS readings, the locality 1 outcrop is located at N 03° 46.290' and E 114° 26.424'. This outcrop consists of 28 meters of limestone exposure that is overlain by 8 meters of clastic sequences (Figure 3.2). The limestone sequence consists of massive and bedded Nummulitic Limestone (Late Eocene) that unconformably overlying the highly folded turbiditic sequences of the Kelalan Formation. The Nummulitic Limestone sequence is overlain by foraminiferal bedded Limestone which was dated as Early Miocene. This Miocene bedded limestone is finally overlain by the Setap Shale equivalent sequence. Calcite veins with several meters long are common in this limestone outcrop (Figure 3.3).

The Nummulitic Limestone interval is made up of larger foraminifera like *Nummulites* spp. and other types of benthic foraminifera. The *Nummulites* spp. has variable size with an average of 1 to 2.5 cm length and 0.5 cm width. These nummulites display rounded to well rounded shape with convex pattern and randomly arranged within the limestone beds (Figure 3.4). Although the Nummulitic limestone normally occurs as a thick and massive limestone bodies, the Nummulitic Limestone here are present as inter-bedded sequence between Nummulitic grainstone and foraminiferal packstone. The limestone was described based on abundantness and intensity of the nummulites. The nummulitic grainstone is made up of predominantly *Nummulites* spp. together with undifferentiated fossils which are present in high density. They formed as cyclicity between limestone rich in nummulite and less abundance of nummulite. Seven of these sequences were observed in the field with an overall fining upward sequence. The packstone consist of less *Nummulites* spp. occurrence. The detailed logging of this outcrop is given in Appendix A.

The lower clastic section is believed to be a part from the Kelalan Formation, which is known as the Temala Member. This Temala Member has been folded slightly, with strike/dip reading on 16°/ U 96° T. The formation is made of sandstone and silty shale of turbidite sequence. Figure 3.5 shows the close-up view of Temala Member at the locality 1 outcrop. In general, the sequence indicates the fining upward sequence and within the sandstone body itself, there is a clearly sequence which is gradually fining upward with the presence of some repetition of lamination (Fig.3.6).

Figure 3.2: The locality 1outcrop that consists of Nummulitic limestone (Late Eocene) , bedded limestone (Early Miocene) and clastic s clastic sequences of the Kelalan Formation (Late Cretaceous) and the Setap Shale equivalent (Miocene)

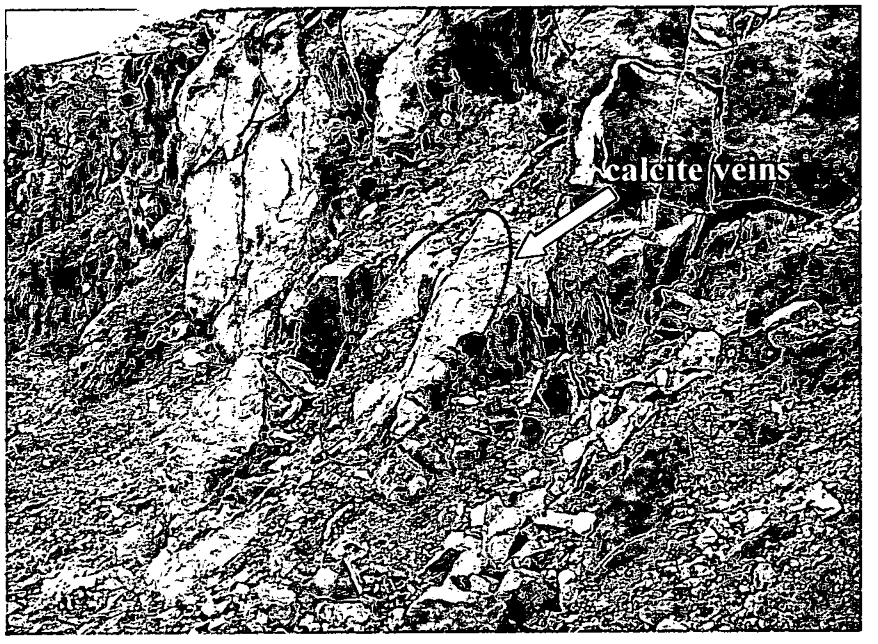

Figure 3.3: The occurrence of some calcite veins (inside the oval shape) that cut through the limestone formation

Figure 3.4: Limestone with abundance of foraminifera types (inside the yellow) with various size and species

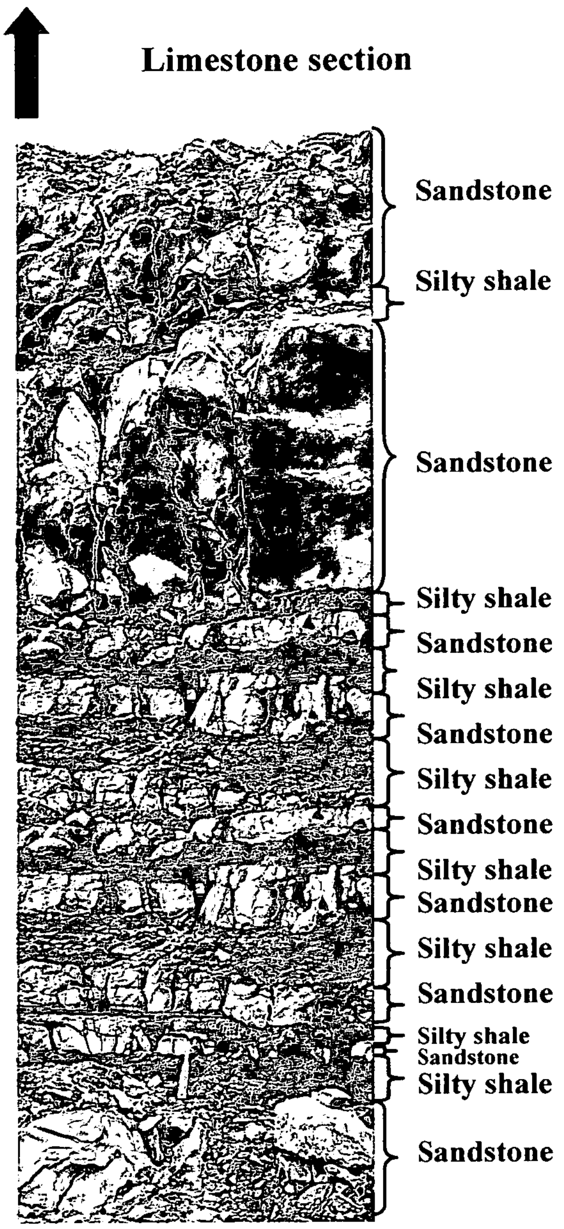

Figure 3.5: The close-up view of inter-bedded sandstone and silty shale of the Temala Member of the Kelalan Formation which is overlain by limestone section

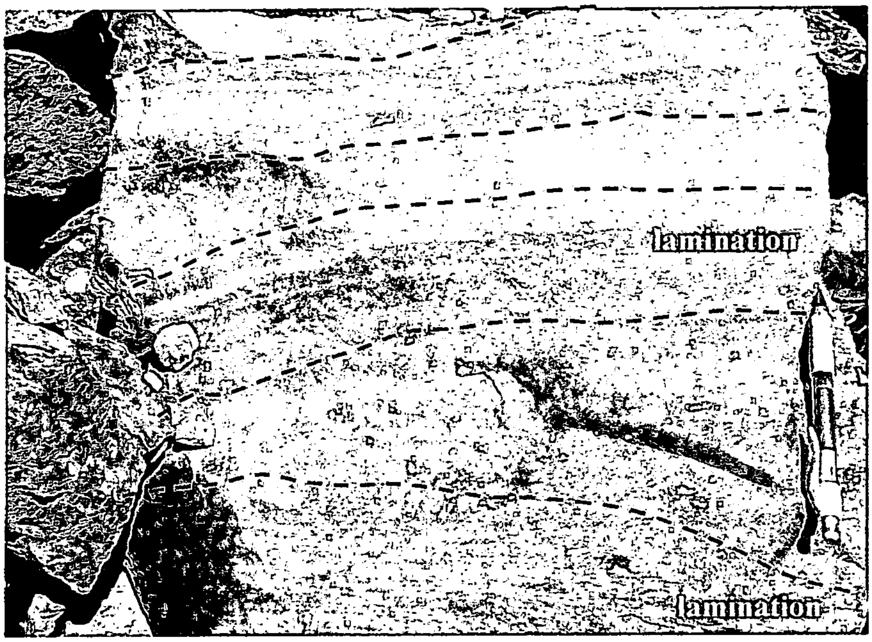

Figure 3.6: The lamination's sequence within the sandstone body

3.4 Locality 2 Outcrop

This outcrop is located at N 03° 46.875' and E 114° 26.298', to the north of the first outcrop. The locality 2 outcrop also shows the presence of limestone (Nummulitic limestone of Late Eocene and bedded limestone of Early Miocene) and clastic sequence of Setap Shale equivalent, similar to the one exposed at locality 1. About 44 meters of limestone and 9 meters of clastic sequence are exposed at this locality (Fig. 3.7). Generally, the limestone is white to grey, very hard, and massive with occurrence of many calcite veins that cross cut the limestone sequences.

The Nummulitic Limestone interval is made up of larger foraminifera like *Nummulites* spp. and other types of benthic foraminifera. The *Nummulites* spp. has variable size. These nummulites display rounded to well rounded shape and randomly arranged within the limestone beds. The Nummulitic limestone here is present as a massive bed, not inter-bedded as seen in locality 1. The limestone was described based on intensity of the nummulites. The nummulitic grainstone is made up of predominantly *Nummulites* spp. together with undifferentiated fossils which are present in high density. The detailed logging of this outcrop is given in Appendix A.

The section is also made up of benthic foraminifera like *Lepidocyclina* spp. and others types of foraminifera. The *Lepidocyclina* spp. is much finer in size with less than 1 cm length, but still recognizable. This Lepidocyclina species is found in sub rounded and platy pattern and distributed randomly in the limestone beds. The limestone has been divided into two types; grainstone and packstone. The limestone of this locality is described based on fossils intensity. The grainstone is made up of *Lepidocyclina-rich* and other fossils. The packstone consists of Lepidocyclina-poor together with other fossils like encrusting algae and bivalve (Fig.3.8).

The clastic section as seen in Fig. 3.6 is part from the Setap Shale Formation. Due to a steepness of the outcrop, the detailed measurement within the clastic sequence was not able to do it. The sequence is made up of alternating sandstone, siltstone, and silty shale. This clastic sequence has been interpreted to be deposited in deeper water turbidite environments.

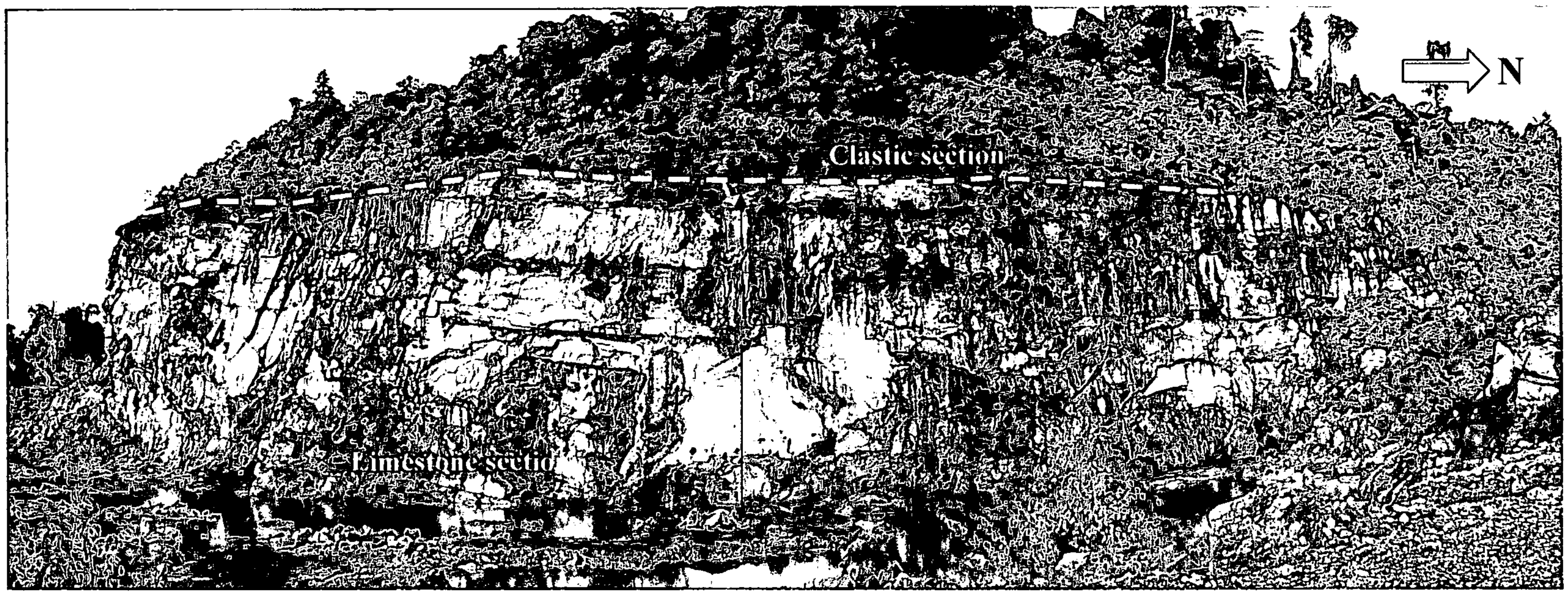

Figure 3.7: The panoramic view of the locality 2 outcrop that exposes the limestone section of Nummulitic Limestone of Late Eocene and bedded limestone of Early Miocene, and clastic section of the Setap Shale equivalent

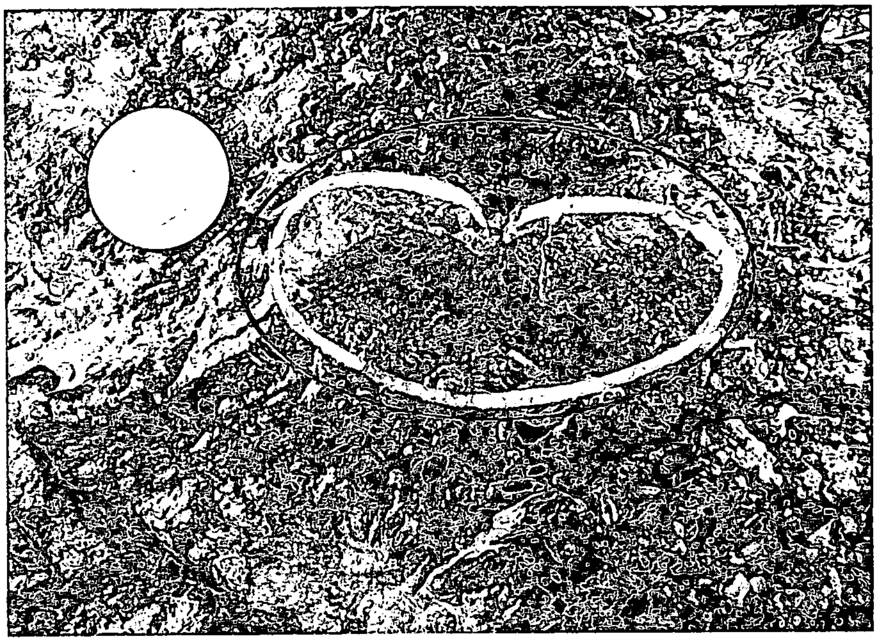

Figure 3.8: The occurrence of bivalve within the limestone at the locality 2 outcrop

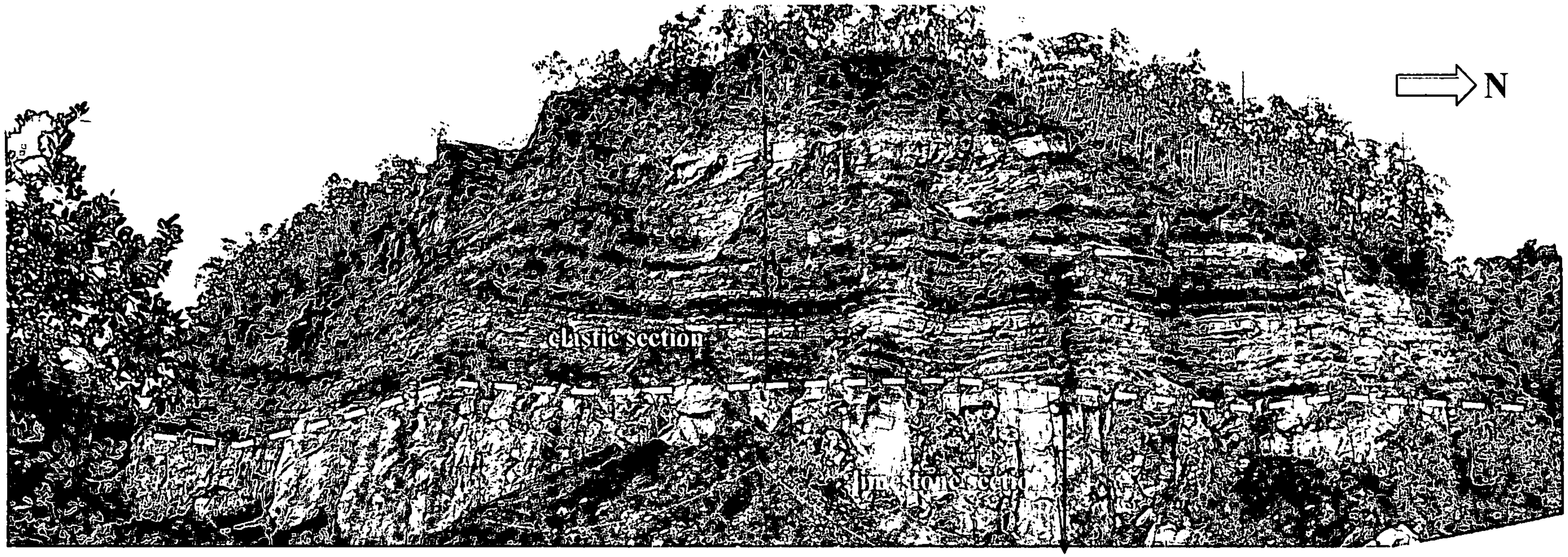

Figure 3.9: The locality 3 outcrop shows the presence of muddy and brecciated limestones of the Early Miocene which are overlain by a thick sequence interbedded shale and sandstone of the Setap Shale equivalent

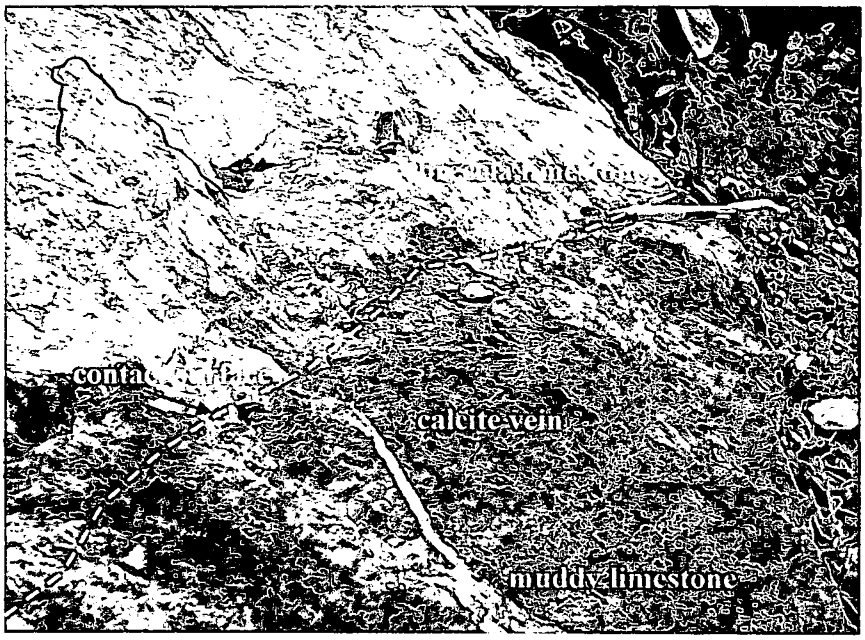

Figure 3.10: The contact surface between muddy limestone (the bottom part) and breccia limestone (upper part)

Figure 3.11: The example of sub-angular rock fragments that are embaded into the limestone to form brecciated limestone

Figure 3.12: The close-up view of sandstone and silty shale beds at locality 3

3.6 General Microfacies and Diagenesis

3.6.1 Locality 1 Outcrop

Four samples (S1-9, S2-9, S2-9 and S4-9) were collected from locality 1 outcrop. Based on field observation and general thin section study, two major types of facies were identified; packstone and grainstone (Figures 3.13, 3.14, 3.15 and 3.16). General thin section analysis of the samples from locality 1 suggests that the limestones are composed of mainly allochems (more than 30%), 10-20% of micrite, and minor amount of porosity. The allochems are made up of various types of microfossils, predominantly larger foraminifera of *Nummulites* spp with the presence of some small benthics and planktonics, fragmented mollusk, *Corraline* algae, and echinoderm spines. The porosity is relatively poor as the pore spaces are obliterated mainly by calcite cements. Table 1 shows the summary of general petrographic study for the locality 1 samples.

The general thin section study also suggests that marine and meteoric diagenesis have occurred within the samples as evidenced by fibrous and equant calcite cements, respectively (Figs. 3.17 and 3.18). Cementation, compaction, and minor dissolution are quite prominent in most samples. Some micrite and the internal parts of the forams have been partially dissolved and replaced by late calcite cements (Fig. 3.17). More examples of thin section figures are given in Appendix B (Plate 1.1 and 1.2).

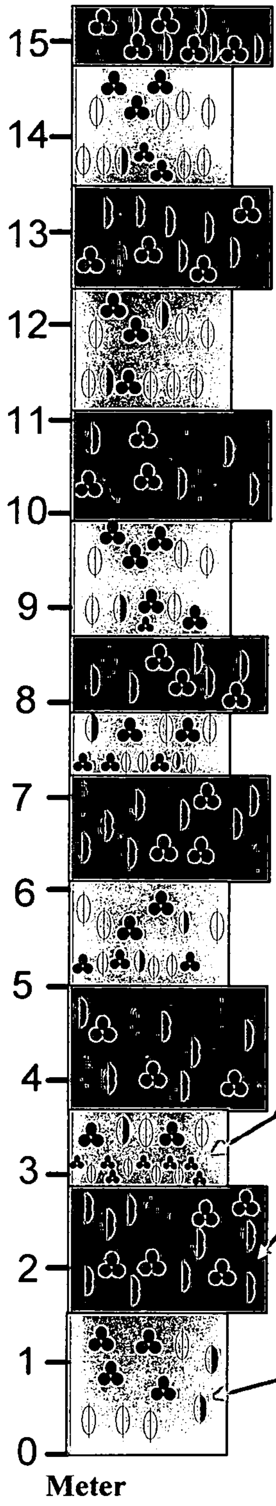

Figure 3.16: Nummulitic grainstone

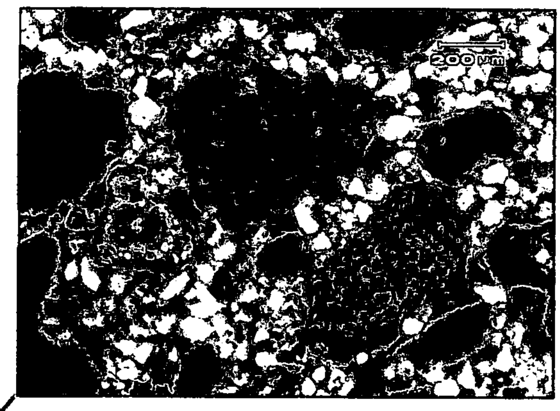

Figure 3.15: Grainstone

Figure 3.14: Packstone

Figure 3.13: The first log shows packstone and grainstone limestone with the presence of variable types of microfossil; 3.14: Packstone; 3.15: Grainstone and 3.16: Nummulitic grainstone

Sample number	Outcrop Lithofacies	Microfacies	Allochem	Micrite	Cement	Φ	Larger foram	Small benthic foram	Plancktonic foram	Molluscs fragment	Echinoderm	Corraline algae
S1-9	Nummulitic Grainstone	Grainstone										
S2-9	Packstone	Grainstone-Packstone										
S3-9	Packstone	Packstone										
S4-9	Grainstpne	Grainstone										

Legend

	Rare (<1%)
	Minor (1-10%)
	Common (10.01-20%)
	Very Common (20.01-30%)
	Abundant (>30.01%)

Table 1: The summary of petrographic study for the locality 1 samples

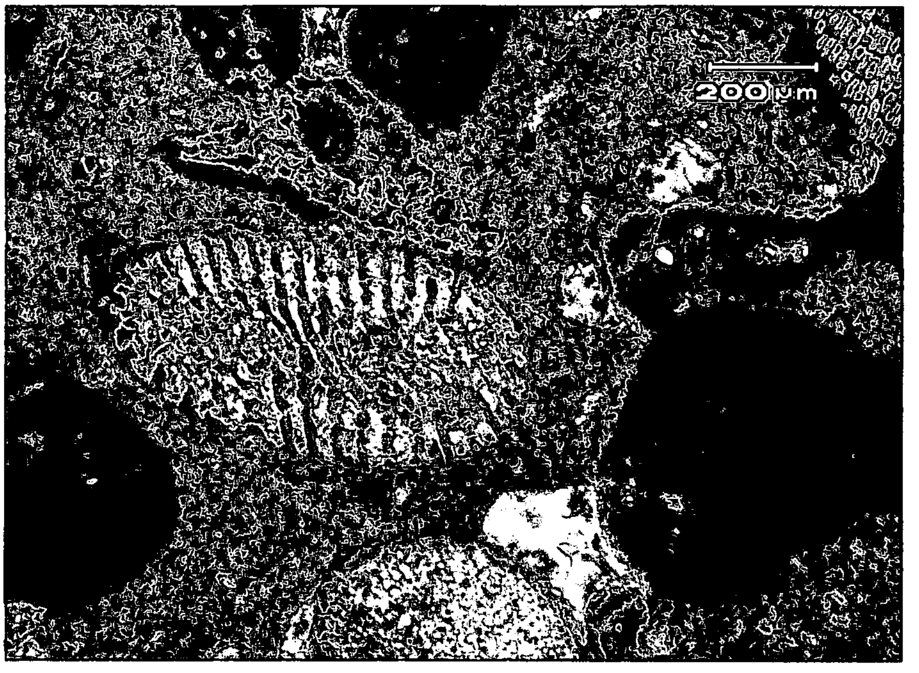

Figure 3.17: Very well rounded allochems floating in the micrite. Some forams have been dissolved and replaced by iron-rich calcite cements

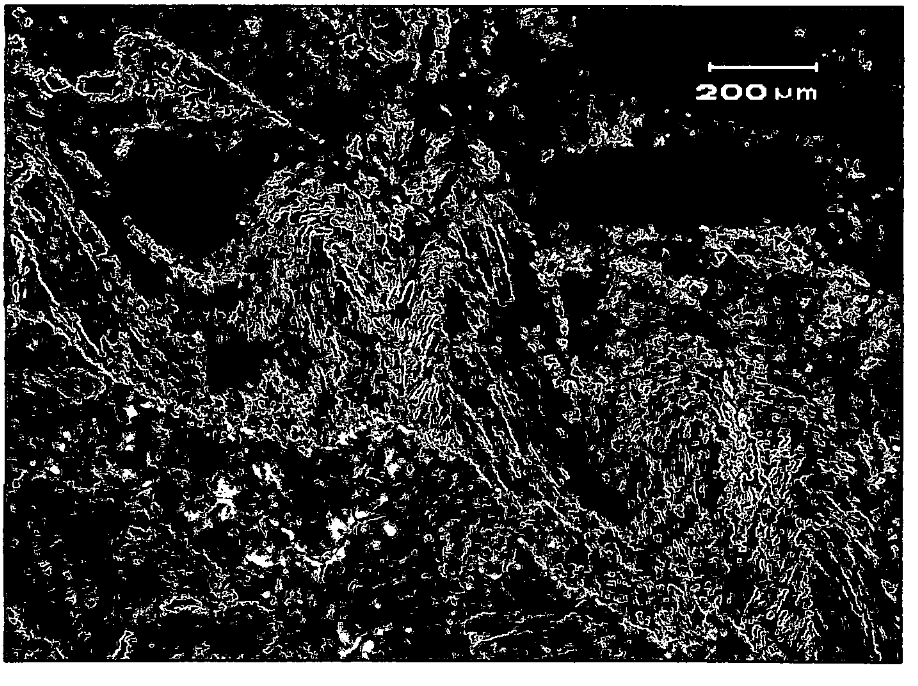

Figure 3.18: Photomicrograph showing bivalve and algae that partially replaced by iron-rich calcite and dolomite cements. Please note that some remnants of calcite (stained in red) as still present

3.6.2 Locality 2 Outcrop

Sixteen carbonate samples were collected from the locality 2 outcrop. Field observation and general thin section analysis (Figs. 3.19, 3.20, 3.21, 3.22, 3.23, and 3.24) show the presence of three general types of limestone; wackestone, packstone and grainstone. Thin section analysis indicates that the samples are comprised of predominantly allochems (exceeds 30%), dominant micrite as a matrix, and variable porosity which is generally poor due to extensive cementation. The allochems are composed of predominantly larger foraminifera such as *Lepidocyclina* spp., *Operculina* spp. and *Amphestigina* spp. The others constituents include small benthic and plancktonic foraminifera, mollusks, echinoderm, red algae, and undifferentiated fossils. The percentage of micrite in wackestone and packstone is generally high (up to 30%) but the percentage of micrite tend be lesser in high energy rocks (grainstones). Generally, the porosity in each sample is relatively low as the cementation is quite extensive. The summary of general petrographic analysis of locality 2 samples is given in Table 2.

The general thin section study suggests that the major diagenetic events that took place within the limestones are cementation, overburden, and minor dissolution. Marine and meteoric diagenesis has occurred within the samples as evidenced by fibrous and equant calcite cements, respectively, in samples S1-6, S2-6, S3-6 and S4-6 (Fig. 3.25 and 3.26). Some forams and matrix/ micrites have been partially dissolved and replaced by calcite and iron-rich calcite and dolomite cements. The additional pictures of thin section are present in Appendix B (Plate 1.3, 1.4, 1.5, 1.6, 1.7 and 1.8).

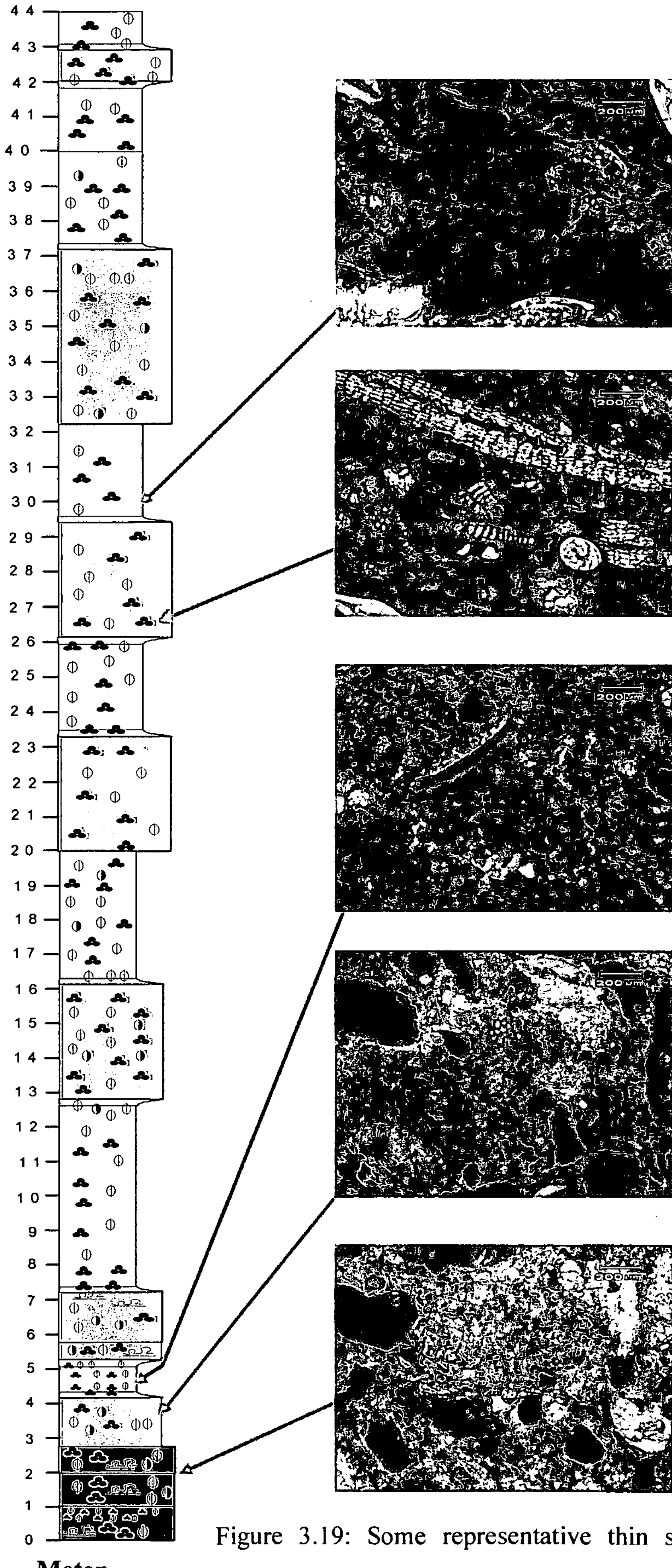

Figure 3.24: Wackestone

Figure 3.23: Packstone

Figure 3.22: Wackestone

Figure 3.21: Packstone

Figure 3.20: Grainstone-packstone

Figure 3.19: Some representative thin section samples from second locality; Figure 3.20: Grainstone-packstone; 3.21: Packstone; 3.22: Wackestone; 3.23: Packstone and 3.24: Wackestone

Sample number	Outcrop Lithofacies	Microfacies	Allochem	Micrite	Cement	Φ	Larger foram	Small benthic foram	Plancktonic foram	Molluscs fragment	Echinoderm	Corraline algae
S1-6	Packstone	Packstone										
S2-6	Packstone	Packstone - Grainstone										
S3-6	Packstone	Packstone - Grainstone										
S4-6	Packstone	Grainstone										
S1-7	Packstone	Packstone										
S2-7	Packstone	Packstone-Grainstone										
S3-7	Packstone	Wackestone-Packstone										
S1-8	Packstone	Packstone-Grainstone										
S2-8	Packstone	Packstone-Grainstone										
S3-8a	Packstone	Packstone										
S3-8b	Packstone	Packstone										
S1-11	Grainstone-Packstone	Grainstone										
S2-11	Grainstone-Packstone	Grainstone										
S3-11	Grainstone-Packstone	Grainstone										
S4-11	Grainstone-Packstone	Grainstone										
S5-11	Grainstone-Packstone	Grainstone										

Legend

	Rare (<1%)
	Minor (1-10%)
	Common (10.01-20%)
	Very Common (20.01-30%)
	Abundant (>30.01%)

Table 2: The summary of petrographic study for the locality 2 samples

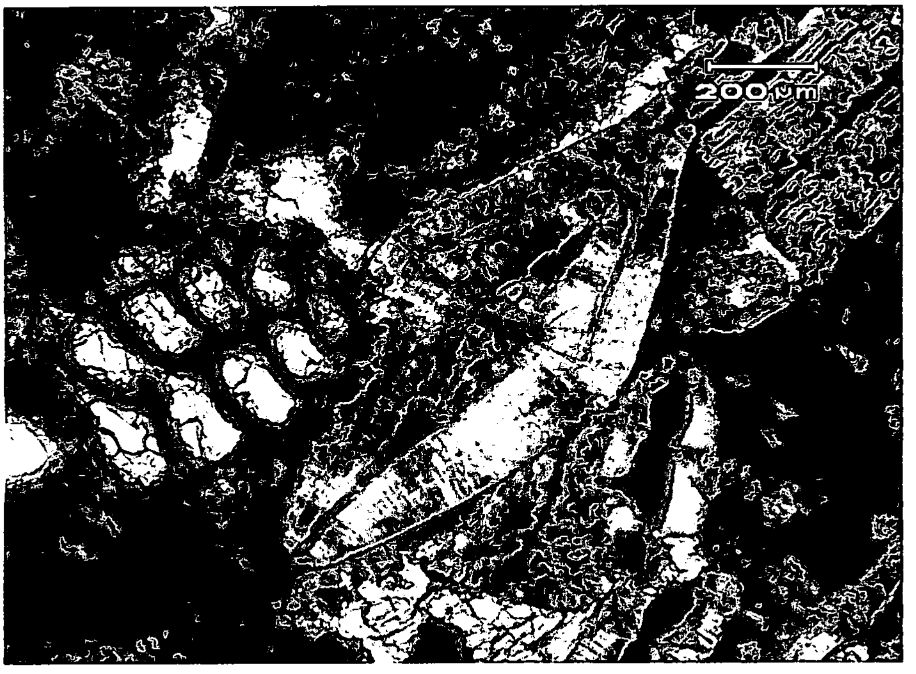

Figure 3.25: Cementation on internal forams and pore spaces has severely affected the properties of the limestone

Figure 3.26: The equant calcite cements have obliterated the pore spaces and responsible for a destruction of porosity and rock properties within the limestone

3.6.3 Locality 3 Outcrop

Four carbonate samples were collected from the locality 3 outcrop. Field observation and general thin section analysis (Figs.3.27, 3.28, 3.29, 3.30, and 3.31) show the presence of three general types of limestone; fossilifereous wackestone, packstone and grainstone. Thin section analysis indicates that the samples are comprised of predominantly allochems (exceeds 30%), dominant micrite as a matrix, and variable porosity which is generally poor due to extensive cementation. The allochems are composed of predominantly larger foraminifera such as *Lepidocyclina* spp in sample S1-2. The others constituents include small benthic and plancktonic foraminifera, mollusks, echinoderm, red algae, and undifferentiated fossils. Planktonics are quite dominant in certain samples, up to 10%, indicating deposition in deeper water environment. The micrite is generally abundant (up to 30%) but the percentage of micrite tend be lesser in high energy rocks (grainstones). Generally, the porosity in each sample is relatively low since the cementation is rather extensive (10%). The summary of general petrographic analysis of locality 3 samples is given in Table 3.

The general thin section study suggests that the major diagenetic events that took place within the limestones are cementation, overburden, and minor dissolution. Marine and meteoric diagenesis has occurred within the samples as evidenced by fibrous and equant calcite cements, respectively (Fig.3. 32). Some forams and matrix/ micrites have been partially dissolved and replaced by calcite cements (Fig. 3.33). More examples of thin section pictures are given in Appendix B (Plate 1.9, 2.0, and 2.1).

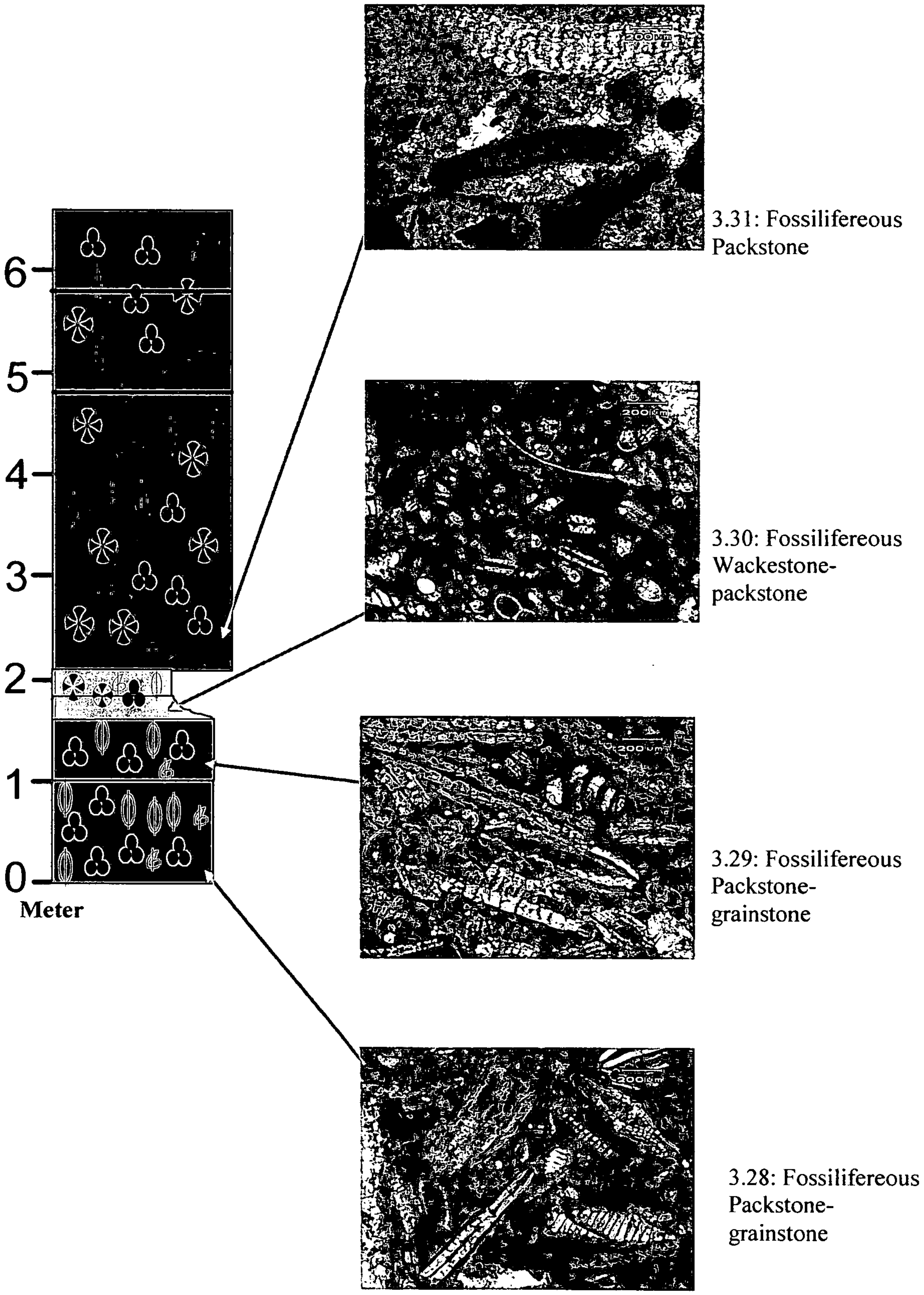

Fig. 3.27: The section indicates several types of fossiliferous limestone at the locality 3;

Fig. 3.28 and 3.29: Fossilifereous Packstone-grainstone; Fig. 3.30: Fossilifereous Wackestone-packstone Fig.3.31: Fossilifereous Packstone

Sample number	Outcrop Lithofacies	Microfacies	Allochem	Micrite	Cement	Φ	Larger foram	Small benthic foram	Plancktonic foram	Molluscs fragment	Echinoderm	Corraline algae
S1-2	Packstone	Packstone-Grainstone										
S2-2	Wackestone	Wackestone-Packestone										
S3-3	Breccia LST	Packstone-Grainstone										

Legend

	Rare (<1%)
	Minor (1-10%)
	Common (10.01-20%)
	Very Common (20.01-30%)
	Abundant (>30.01%)

Table 3: The summary of general petrographic study of the samples from the locality 3 outcrop

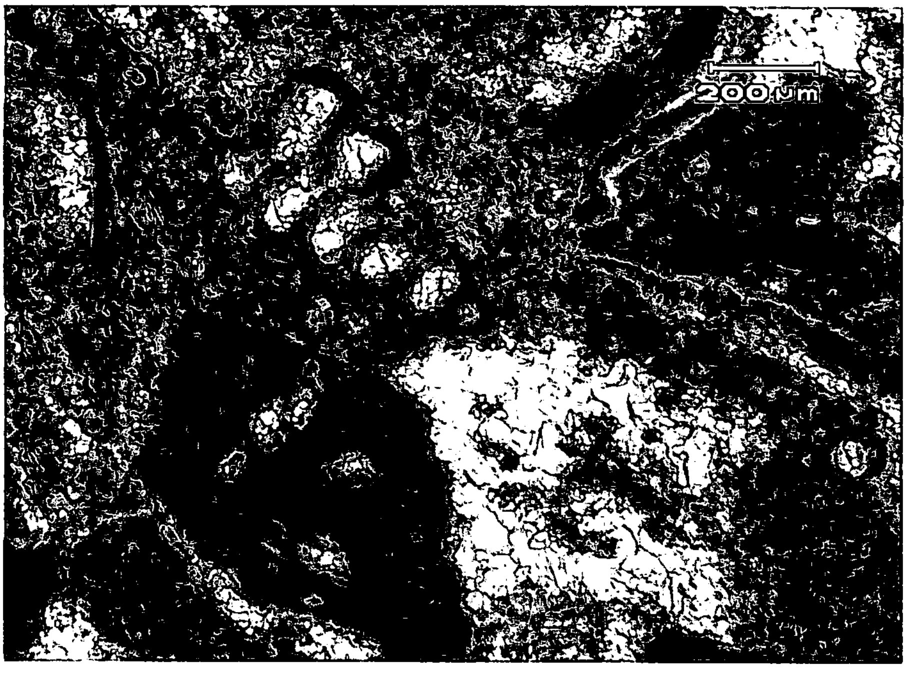

Figure 3.32: Photomicrograph showing the benthic as a major constituent within the limestone. Please note the presence of extensive calcite cements

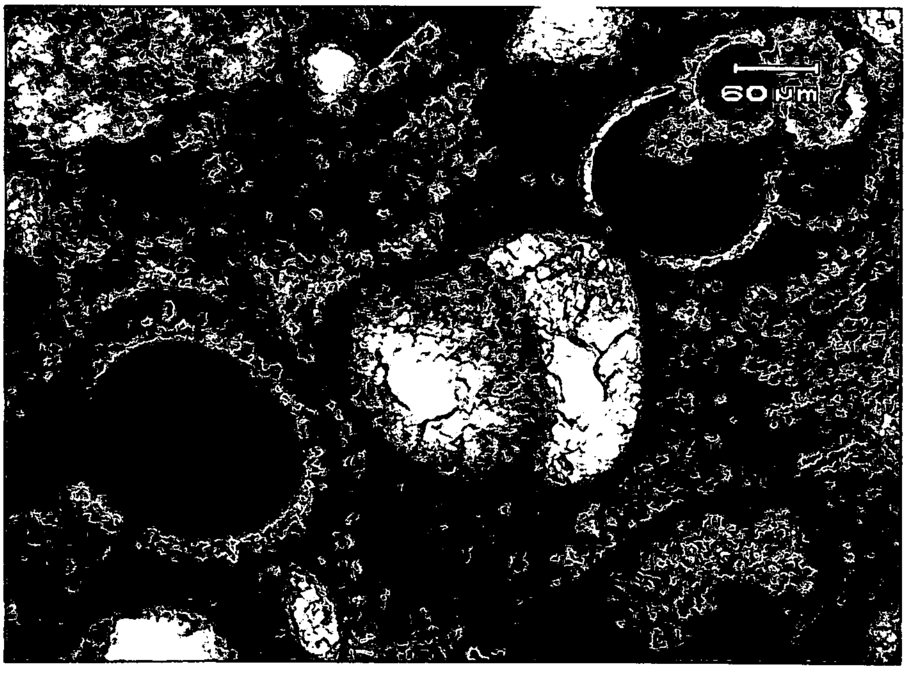

Figure 3.33: Photomicrograph showing the abundance of planktonic forams within the sample indicating deposition in deeper water environment

3.7 Sequence Stratigraphy

3.7.1 Locality 1 Outcrop

Based on general analysis of the sedimentary sequence, two system tracts were interpreted at the locality 1. The lower sequence of the limestone is made up of transgressive systems tract (TST). A major sequence boundary (SB) was interpreted at the base of the Nummulitic Limestone (Late Eocene) at the contact with the clastics of the Kelalan Formation (Late Cretaceous). The TST reached the peak as a maximum flooding surface (MFS) as evident by the fining upward nature and highly presence of deeper water microfossils within the limestone. This sequence is then followed by a progradation and shown by a series of coarsening upward packages. These packages have been assumed to represent the high system tract (HST). Another sequence boundary (SB) surface was interpreted at the boundary between the Early Miocene fossilifereous limestone and the Late Eocene of the Nummulitic Limestone sequences. The general sequence stratigraphic framework of the sequences at the locality 1 is given in Fig. 3.34.

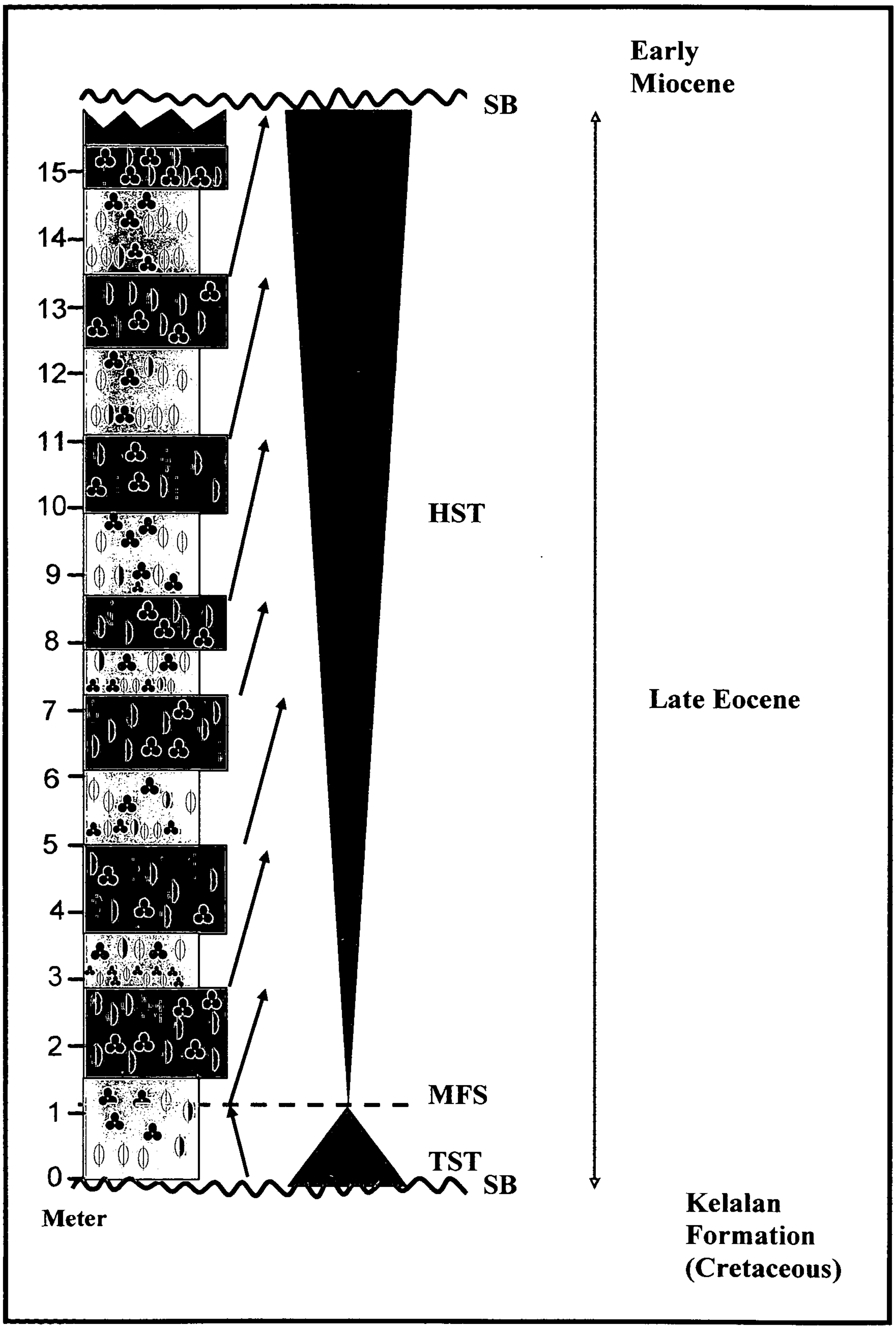

Figure 3.34: General sequence stratigraphic framework of locality 1

3.7.2 Locality 2 Outcrop

The sequences exposed at locality 2 show the presence of two major system tracts; transgressive system tract (TST) and high stand system tract (HST). The sequence had first developed as TST package and later bounded by a sequence boundary (SB). The lower sequence of the limestone is made up of transgressive systems tract (TST). A major sequence boundary (SB) was interpreted at the base of the Nummulitic Limestone (Late Eocene) at the contact with the clastics of the Kelalan Formation (Late Cretaceous). This TST package was interpreted to occur when there is an increase in sea-level during a particular period. The sequence is often shows fining upward sequence with the presence of deeper water microfossils. When the sea-level reaches its peak and floods the whole the vicinity, this event may represent the maximum flooding surface (MFS) that usually occurs at the top of the TST. This sequence has then changed to a series of progradation with series of coarsening upward sequences that have been interpreted to represent the HST that occur during the beginning of sea-level fall or when the there is an increase in carbonate production during a stagnant sea-level. The progradation is terminated when the sea water level began to increase. The HST is split up by another sequence boundary (SB), and the another TST started to develop. Another sequence boundary (SB) surface was interpreted at the boundary between the Early Miocene fossiliferous limestone and the Late Eocene of the Nummulitic Limestone, similar to the one shown at locality 1. The general sequence stratigraphic development at locality 2 is shown in Fig. 3.35.

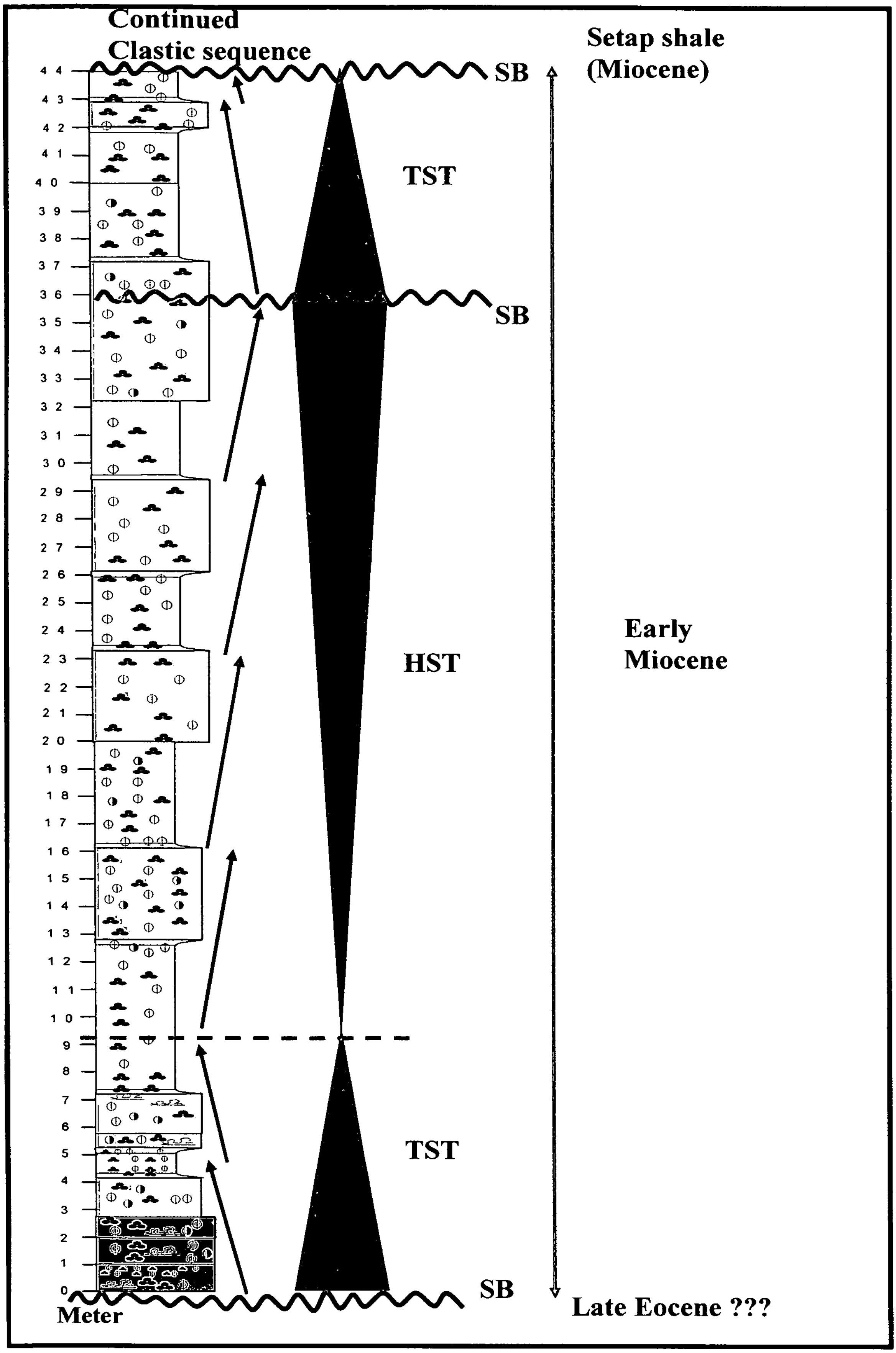

Figure 3.35: General sequence stratigraphic framework of locality 2

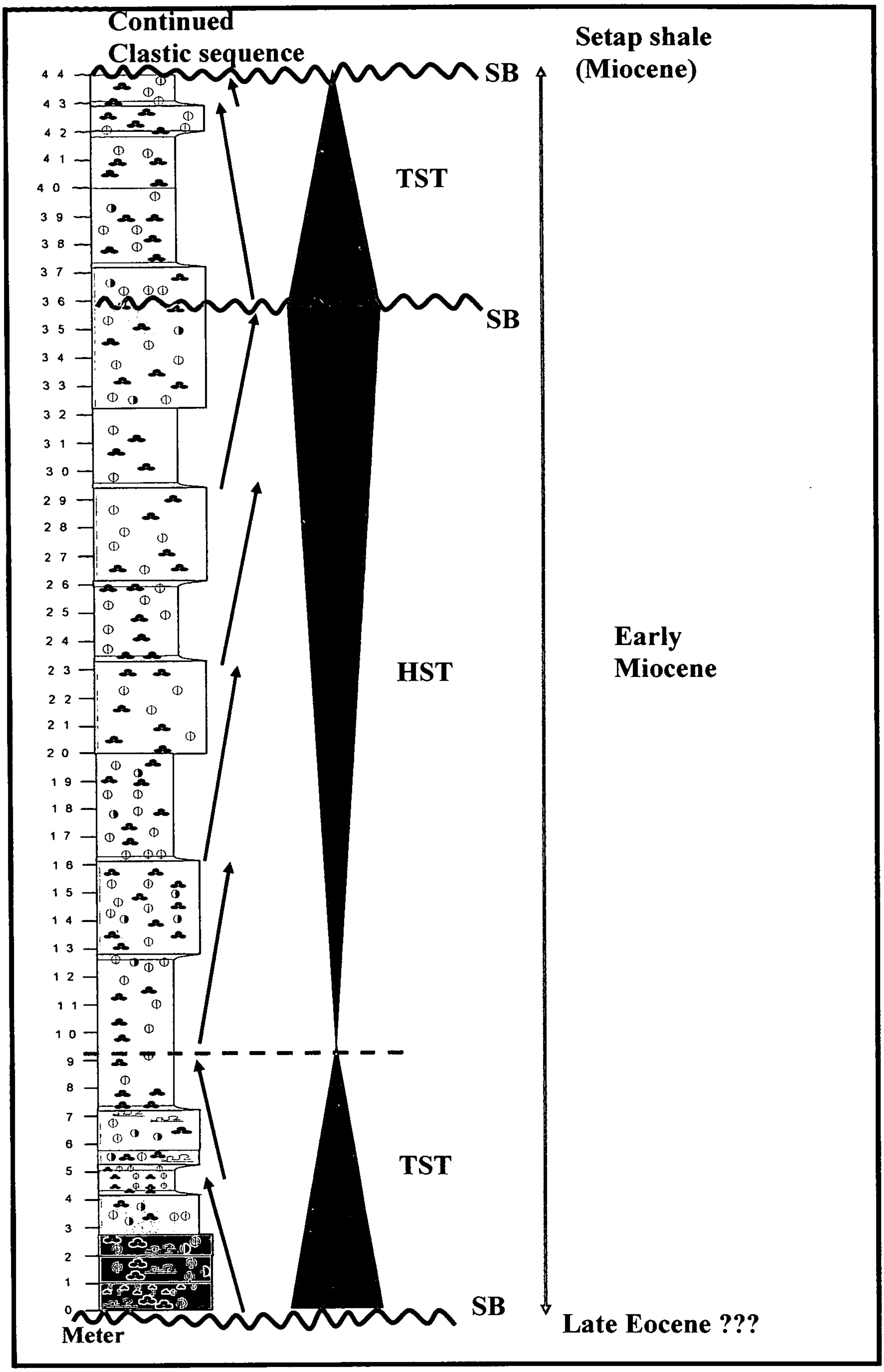

Figure 3.35: General sequence stratigraphic framework of locality 2

3.7.3 Locality 3 Outcrop

The sequence stratigraphic interpretation at locality 3 was made based on sequence development pattern (coarsening vs fining upward sequence) coupled with the presence of the fossil and microfossils. As indicated earlier on, the locality 3 outcrop just represents the Early Miocene carbonate section which is overlain by a thick clastic sequence of the Setap Shale equivalent. The observation on the exposed section suggests that the sequence started as a transgressive system tract (TST) with recognition of MFS surface towards the top and continued as the high stand system tract (HST) packages. Similar to observation at localities 1 and 2, the TST is signed within the sequence as the densely occurrence of deeper water microfossils within the fining upward sequence. During the MFS, it was assumed to be the highest sea-level that provided favourable and conducive environments for those forams to live. After attaining the maximum flooding, the limestone continued to prograde back during the HST/LST. At this period, the sea-level began to decrease and consequently dropped. This HST continued until the termination by another sequence boundary (SB) at the top of limestone sequence that separates the limestone from the overlying clastic sequence. The general sequence stratigraphic framework at locality 3 is illustrated in Fig. 3.36.

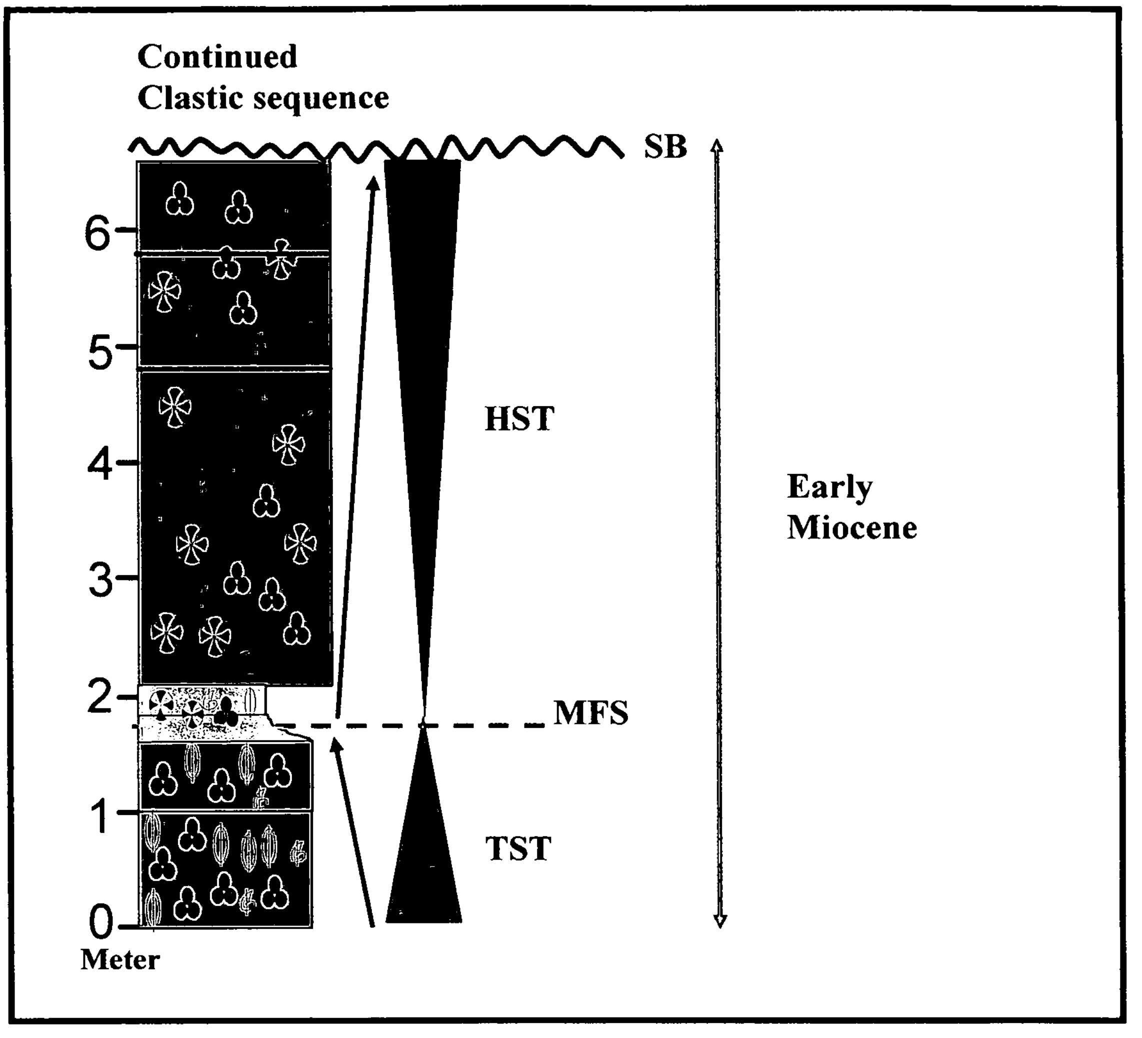

Figure 3.36: Sequence stratigraphic framework of locality 3

3.8 Correlation of Sedimentary Sequences of Localities 1, 2 and 3

The general stratigraphic and sequence development correlation was made by tieing up the data, age, major surfaces, and interpretation from all localities together. Basically, the Kelalan Formation of the Late Cretaceous has been observed at localities 1 and 2 while the Late Eocene part has been recognized at the first and second localities. The Early Miocene has been observed in all localities. The youngest clastic sequence of the Setap Shale equivalent has been observed in all localities.

Generally, a major hiatus and unconformity has occurred at the boundary between the Upper Cretaceous of the Kelalan Formation (Temala Member) and the Late Eocene of the Melinau Limestone. This hiatus shows the missing section of the Paleogene- Middle Eocene sediments that represents about 20 million years equivalent. Similarly, another hiatus and disconformity has been observed at the boundary between the Nummulitic Limestone (Late Eocene) and Fossilifereous Limestone (Early Miocene), suggesting that the missing of the Oligocene sequences in the study area. These two major hiatus may suggest the uplifting of the area, followed by the erosion of the sediments prior to sedimentation of the overlying sediments or formations. The general correlation of sequence development and sequence stratigraphic framework of the area is given in Fig. 3.37.

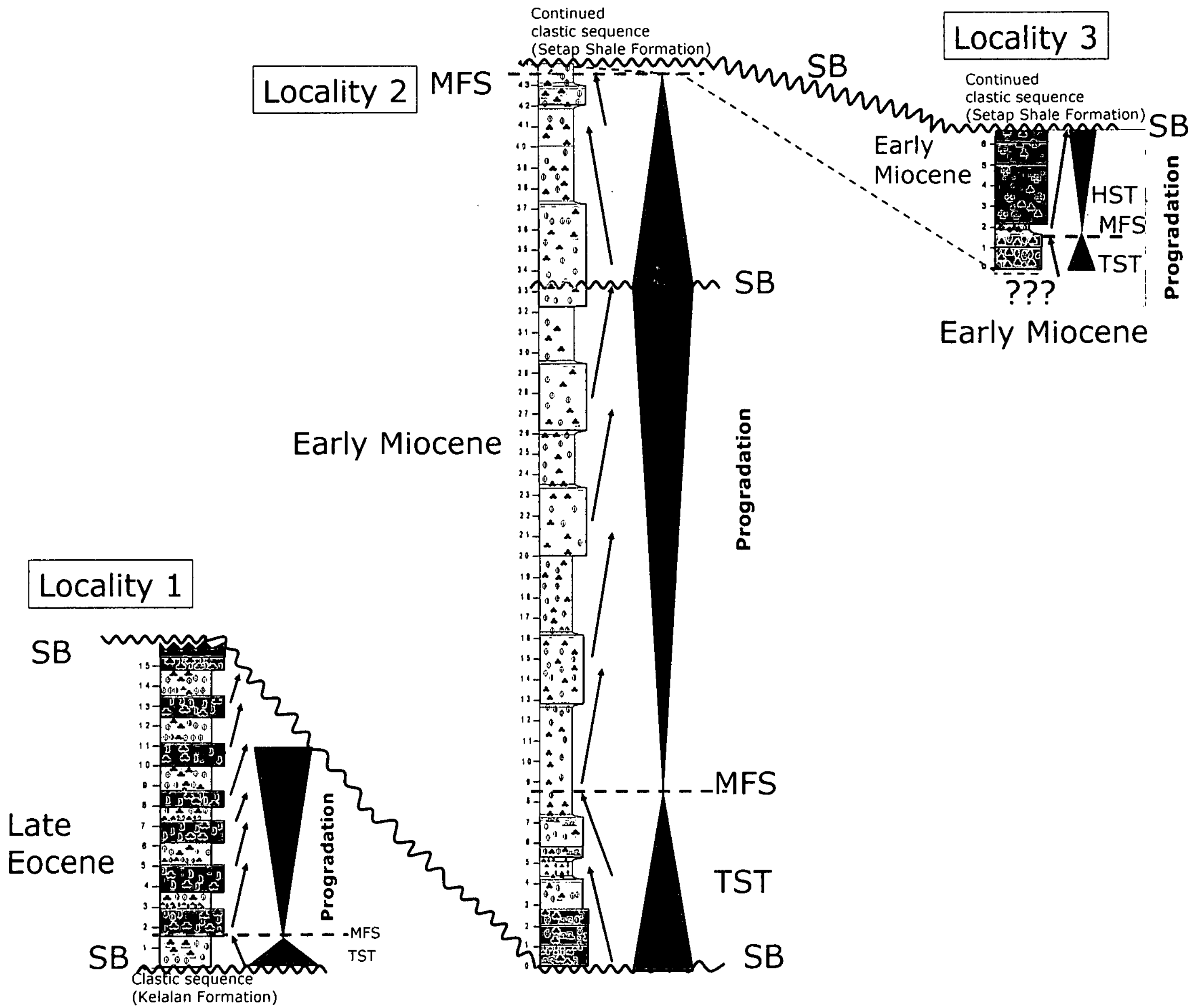

Figure 3.37: General correlation of sequence development and sequence stratigraphic framework of the study areas

3.9 Depositional Environment Interpretation

The depositional environment interpretation of the study area was made based on sedimentary features and sequence development of the limestones. At the first locality, the inter-bedded between *Nummulites* spp. dominated and muddy limestone beds suggests the deposition within the bank to middle-outer basinal areas. The thick and massive nummulic limestone suggests deposition within the very shallow water bank area. Generally, the Nummulitic Limestone of the Late Eocene sequence was interpreted to be deposited as bank deposits and extended towards to the inner and outer part basin (Fig. 3.38).

The variable fossilifereous limestones of the Early Miocene as seen at various localities suggests the deposition ranging between reef core to basinal-distal slope areas. The brecciated limestone as seen at locality 3 may suggest deposition and transportation along the slope and finally deposited toward the distal slope and basinal areas. This is strongly supported by the presence of abundant planktonics. The presence of corals heads suggests the deposition closer to reef core area while the presence of many branching corals indicates deposition within the middle part of the slope.

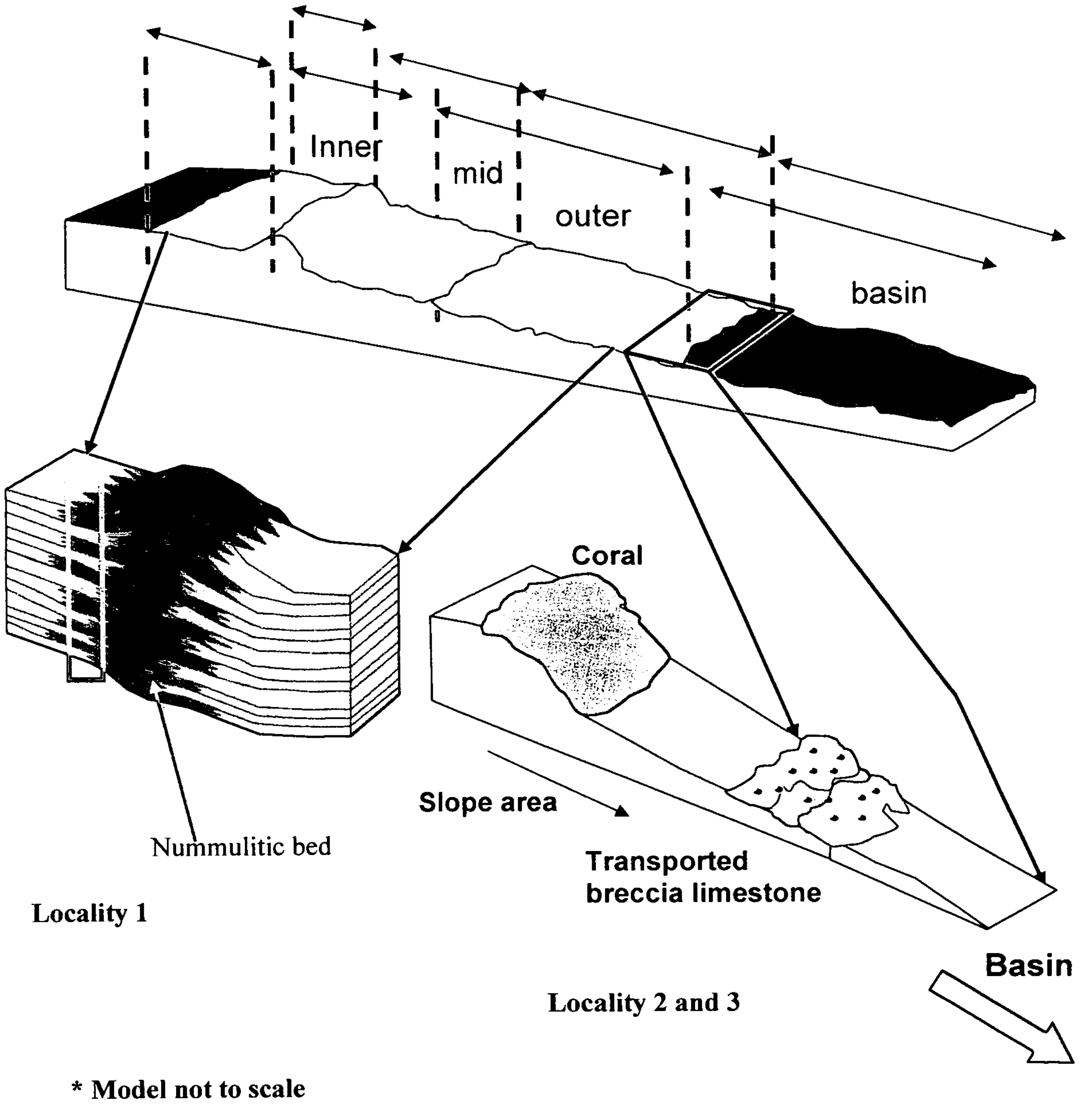

Figure 3.38: The illustrated depositional model of locality 1, 2, and 3, shows the extending depositional environment, from the bank deposits until the outer part of basin

CHAPTER 4 : CONCLUSIONS

4.1 Conclusions

Based on the study carried out in the Batu Gading area, it is concluded that:

1) The Batu Gading Limestone is comprised of the Nummulitic Limestone (Late Eocene) and the Fossilifereous Limestone (Early Miocene). The Nummulitic Limestone has a total thickness of about 28m that conformably overlain the highly folded formation of the Temala Member of Kelalan Formation (Cretaceous?) and present at localities 1 and 2. The Palaeocene sediments have been either non-deposited or eroded away. The Fossilifereous Limestone of the Early Miocene sequence equivalent to the Melinau Limestone has a total thickness of about 50 m and disconformably overlain the Nummulitic Limestone sequence. They are present at all localities 1,2 and 3. The Early Miocene limestone was terminated by the clastic section of the Setap Shale.

2) The Batu Gading Limestone had several transgressive system tracts (TST) and high system tracts (HST) as implied from the sedimentary sequences. Several sequence boundaries were also identified within the sequences. The major SBs were recognized at the boundaries between the Kelalan Formation (Late Cretaceous) and the Nummulitic Limestone (Early Miocene) and also between the Nummulitic Limestone (Late Eocene) and Fossilifereous Limestone (Early Miocene). Disconformity surface was also observed at the boundary between the Fossilifereous Limestone and the overlying clastic sequence of the Setap Shale equivalent. Another SB was recognized at the second locality that separates the HST and TST.

3) Two major limestones were observed; the Nummulitic Limestone (Late Eocene) and Fossilifereous Limestone (Early Miocene). The Fossilifereous limestone could be further subdivided into breacciated limestone, lepidocyclina limestone, and other fossilifereous limestone. Generally, three types of limestone were recognized in the field based on Dunham's classification; grainstone, packstone and wackestone. These lithologies have abundant foraminifera and larger foraminifera beside some other allochems.

The limestones consist of many fossils such as the large *Nummulites* spp., *Lepidocyclina* spp., also the mollusks (bivalve) and algae (*Rhodolith*). Thin section observation shows tremendous amount of species and predominantly benthonic foraminifera like *Operculina* spp., *Amphestigina* spp., *Textularid* spp., *Discocyclina* spp., and plancktonic foraminifera namely *Globegerina* spp with some undifferentiated coral, *Corraline* red alage, fragmented mollusks and sporadically *Miliolid* spp. The limestones have generally contain high percentage of allochems and micrite and generally show very low porosity and permeability.

4) The Nummulitic Limestone (Late Eocene) sequences have been interpreted to be deposited as bank deposits in a ramp setting? as indicated by the presence of very massive Nummulitic Limestone bed. The inter-bedded between the Nummulitic Limestone and muddy limestone suggests that the deposited occurred within the bank areas and extended further to outer part of basin similar to one found in the El Garia Formation, in Tunisia. Although the study area could be a part of the ramp setting but it still enigmatic as the area does not cover a very large area. In contrast, the Fossilifereous Limestone (Early Miocene) was deposited as reef core, slope up to distal slope as suggested by the presence of massive coral heads (reef core), massive, platy, and branching corals (slope deposits) and breacciated limestone (distal slope of basinal areas). The second and third localities suggest more distal as compared to the first locality. The presence of plancktonic foraminifers suggests the environment should be at the deeper area in the basinal areas.

5) Diagenesis has affected the limestone quite significantly. As a result, the porosity is relatively very low due to extensive compaction and calcite and dolomite cementation. Fibrous cement indicates a marine water diagenesis while the presence of equant calcite suggests precipitation within a fresh water environment.

6) The Nummulitic Limestone (Late Eocene) of bank deposit is the best reservoir for exploration. The inter-bedded Nummulitic Limestone and muddy

limestone provides a good basis for subdivisions of the massive Nummulitic beds for reservoir geological modeling.

4.2 Limitations and Recommendations

There are several limitations that hinder the development of a good study.

1) Limited exposures within a reasonable distance limit our interpretation in terms of lateral facies changes and variation, architectural variability and reservoir continuity. Moreover, the area covers a quarry sites that limit our movement from one locality o other localities. Blasting activities also limit our movement as many areas are considered as restricted zones. Furthermore, the blasted areas are very dangerous as the rocks could collapse at any time.

2) Many samples were collected for the study. However, only selected few could be prepared and analyze due to time constraints of the project. These would limit the scope and quality of the interpretation particularly in sequence stratigraphy and diagenesis. Moreover, the methods used for diagenesis would also limit the interpretation on diagenesis.

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APPENDIX A

FOSSILS, ACCESSORIES &SEDIMENTARY STRUCTURES

- Macrofossil frags., undiff.
- Macrofossil frags., rounded
- Macrofossil, whole
- Microfossil, undiff.
- Macro/microfossil, encrusting
- Algae, undiff.
- Algae, Red
- Algae, Green
- Encrusting red algae
- Branching red algae
- Algal balls, oncolites, rhodoliths
- Bryozoa
- Corals, colonial
- Corals, solitary
- Massive coral (Porites)
- Echinoderms
- Foraminifera, undiff.
- Foraminifera, pelagic
- Foraminifera, small benthonic
- Foraminifera, large benthonic
- Molluscs, undiff.
- Gastropods
- Pelecypods (clams)
- Ostracods
- Plant remains
- Sponges
- G Glauconite
- H Hematite
- Oolites
- Organic matter

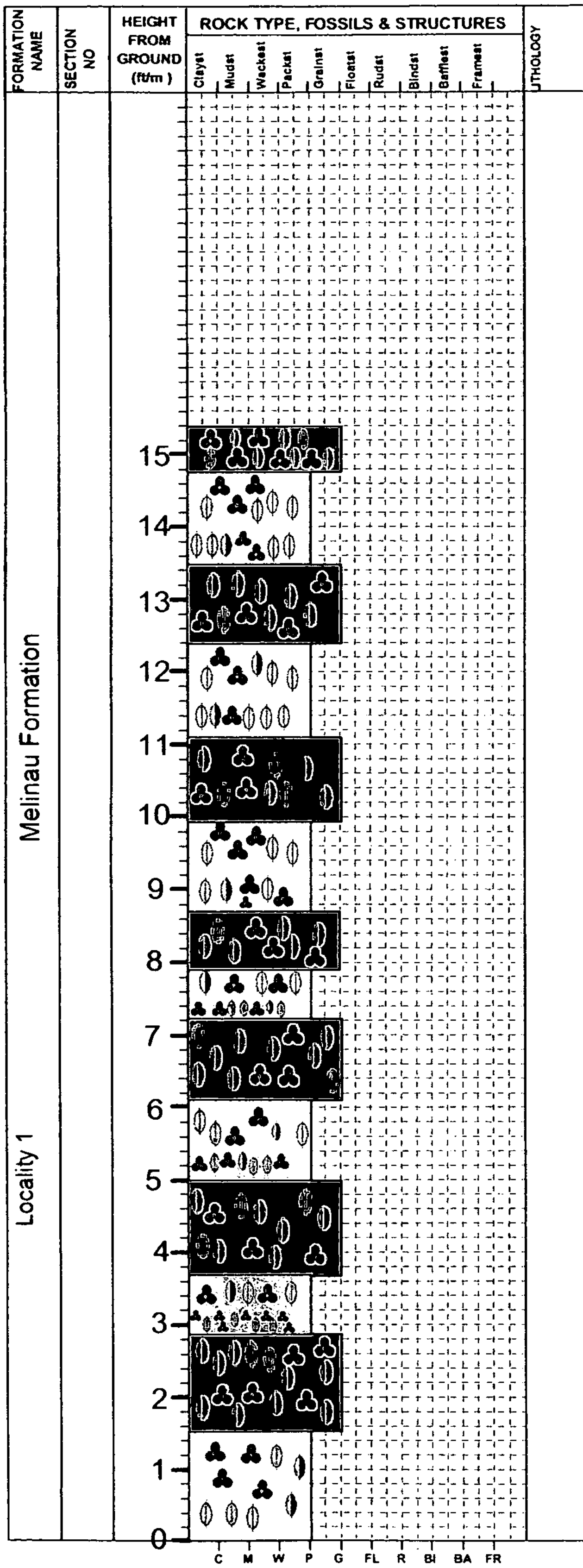
- mm/cm/dm/m Parallel stratification
- Cross-bedding (general)
- Irregular bedding
- Graded bedding
- No apparent bedding
- Nodular bedding
- a/i/s Ripple marks (asym./interf./sym.)
- Pull-over flame structure
- Scour and fill
- s/m/w Burrowed (slightly, mod, well)
- Churned
- Bored
- Bored surface
- Plant root tubes
- Mud cracks
- Slump structures/contorted beds
- Convulate bedding
- Load cast
- Tepee structure
- Birdseye, fenestral fabric
- Breccia, solution, collapse
- Dissolution - cpction (horse tail)
- Stylolite
- Fractures
- Slickensides
- Geopetal fabric
- Vadose silt
- Phospate nodules
- Pyrite
- Quartz grains (floating)
- Siderite grains
- Chert

TRACE FOSSIL ABBREVIATION

Ar	*Arenicolites*	***Pa***	*Paleophycus*
As	*Asterosoma*	***Pl***	*Planolites*
Ch	*Chondrites*	***Ry***	*Rhyzocorallium*
Co	*Conichnus*	***Sk***	*Skolithos*
Cy	*Cylindrichnus*	***T***	*Thalassinoides*
D	*Diplocraterion*	***Te***	*Teichichnus*
H	*Helminthopsis*	***Tr***	*Terebellina*
O	*Ophiomorpha*	***Z***	*Zoophycos*

OUTCROP LOGGING SHEET (Carbonates)

LOCATION/GPS READING: Locality 1 **GEOLOGIST:** ________ **DATE:** 27/08/2007 **SHEET NO. :** ___ **of** ___



DESCRIPTIVE NOTES

This section contains a lot of *Nummulites* spp, the arrangement of *Nummulites* spp is in a random pattern. The average size of *Nummulite* is 2-3 cm. The lithology is grey in color

Grey in color, contains less of *Nummulites* spp., but still preserved various types of fossil,mostly foraminifers. The foraminifera are very fined, some of them undifferentiated, the limestone is grey in color

This section contains a lot of *Nummulites* spp, the arrangement of *Nummulites* is in a random pattern. The average size is 2-3 cm. The lithology is in grey color

The sequence is more less with the initial part. Basically, the section is like a coarsening upward sequence. Less dense of *Nummulites spp.*, but still preserved various types of fossil, very fined fossil (almost foraminifera)

This section contains a lot of *Nummulites* spp,the average size is 2-3 cm (length). No arrangement for *Nummulites* spp. distribution. The limestone is grey in color. Some presence of calcite veins on the limestone surface

The sequence is more less with the previous part. Basically, the section is like a coarsening upward sequence. Less dense of *Nummulites spp.*, but still embodied various types of fossil,undifferentiated,very fined fossil (almost foraminifera)

This section contains a lot of *Nummulites* spp, the arrangement of *Nummulites* is in random pattern. The average size of Nummulite is 2-3 cm (length). The limetone is grey in color. Some calcite veins found on the limestone surface

Less dense of *Nummulites spp.*, but still preserved different types of fossil, undifferentiated and very fined fossils (almost foraminifera). The limestone is grey in color

This section contains a lot of *Nummulites* spp. No such arrangement for the *Nummulites* spp distribution. The *Nummulites* spp. size is about 2-3 cm. The limestone.is grey in color

The limestone is grey in color. Less dense of *Nummulites spp.*, but still contains several types of fossil-undifferentiated very fined fossils (almost foraminifera). Some presence of calcite veins on the limestone surface

Same as the second bed. The limestone is grey in color. Containing abundant of *Nummulite* spp. with average size about 1-3 cm, could be the repetition of sequence (same as sequence from bed 1-2)

The sequence is more less with the initial part. Basically, the section is like a coarsening upward sequence. Less dense of *Nummulites spp.*, but still contains different types of fossil, undifferentiated and very fined fossils (almost foraminifera). Calcite veins found on the limestone surface

This section contains a lot of *Nummulites* spp. No arrangement for the *Nummulite* distribution. The average size of Nummulite is 2-3 cm (length). The limestone is grey in color. This section still preserved some very fined-undiffenanted fossils

Thus section is grey in color, massive, hard and dense. Less dense of *Nummulites* spp. but preserved various types of foraminifera,very fined in size. Some calcite veins found on the limestone surface.

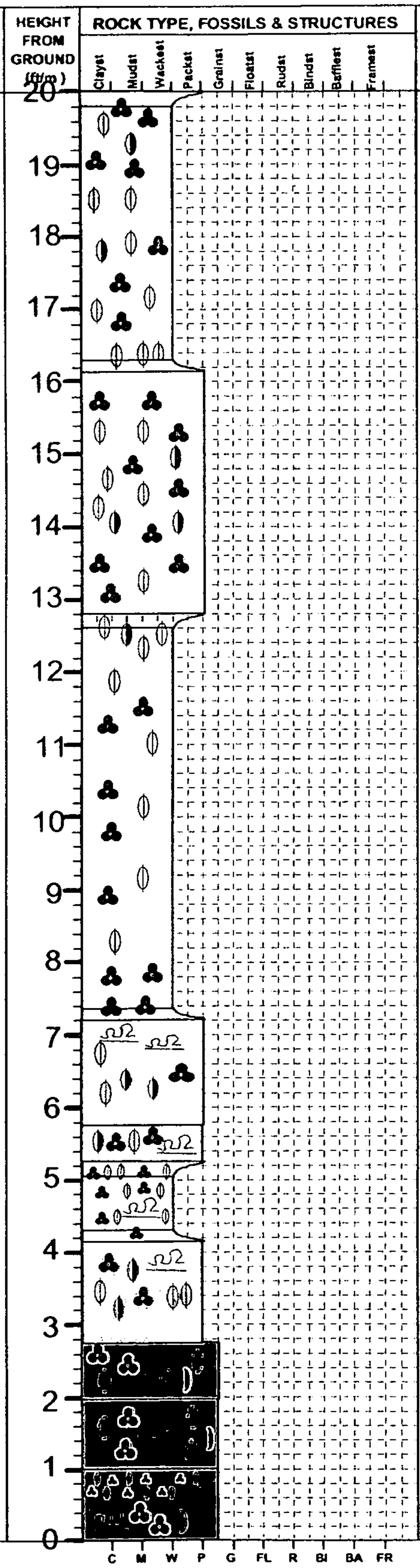
OUTCROP LOGGING SHEET (Carbonates)

LOCATION/GPS READING: Locality 2 GEOLOGIST:________ DATE: 27/08/2007 SHEET NO. :___ of __

FORMATION NAME: Melinau Formation

SECTION NO: Locality 2

HEIGHT FROM GROUND (ft/m) | ROCK TYPE, FOSSILS & STRUCTURES | LITHOLOGY | DESCRIPTIVE NOTES



DESCRIPTIVE NOTES

Grey and fined limestone. Contains different types of foraminifera (undifferentiated)

Grey limestone, contain encrusting algae, dense with *Lepidocyclina* spp, various type of fossil (unidentified & identified)

Grey and fined limestone,contains different types of foraminifera (undifferentiated), mollusks (bivalve)

Grey limestone, mixture of different types of foraminifera, algae (encrusting). Thus like a bedded limestone. Fossil distributed randomly, no arrangement

Grey limestone; contain encrusting algae in various size, *Lepidocyclina* spp.,undifferentiated foraminifera, mollusks other types of fossil

Grey limestone, contains encrusting algae with size 2-3 cm including different types of foraminifera (unidentified & identified), dense with *Lepidocyclina* spp.

This section is grey in color, contains encrusting algae (*Rhodolith*), size 3-4 cm (length), different types of foraminifera. Very dense with *Lepidocyclina* spp.

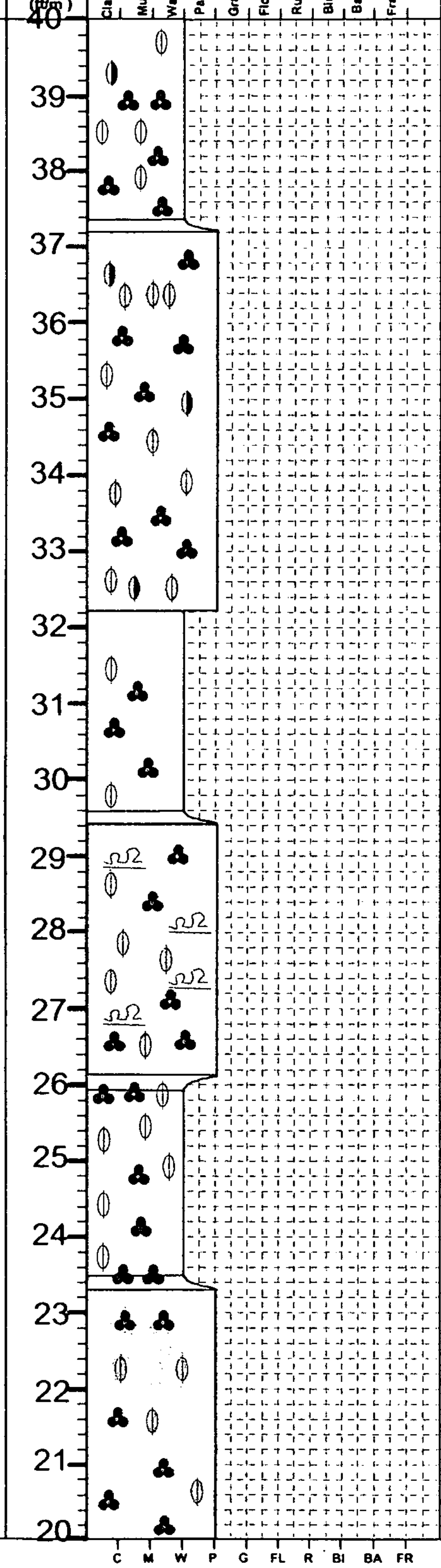
OUTCROP LOGGING SHEET (Carbonates)

LOCATION/GPS READING: Locality 2 GEOLOGIST:________ DATE: 27/08/2007 SHEET NO. :___ of ___

FORMATION NAME	SECTION NO	HEIGHT FROM GROUND (ft/m)	ROCK TYPE, FOSSILS & STRUCTURES (Clayst, Mudst, Wackest, Packst, Grainst, Floatst, Rudst, Bindst, Bafflest, Framest)	LITHOLOGY	DESCRIPTIVE NOTES

Melinau Formation

Locality 2



Grey and fined limestone,contains different types of foraminifera (undifferentiated), mollusks (bivalve)

Grey limestone; contain encrusting algae in various size, *Lepidocyclina* spp.,undifferentiated foraminifera, mollusks other types of fossil

Grey limestone, mixture of different types of foraminifera, algae (encrusting). Thus like a bedded limestone. Fossil distributed randomly, no arrangement

Grey limestone; contain encrusting algae in various size, *Lepidocyclina* spp.,undifferentiated foraminifera, mollusks other types of fossil

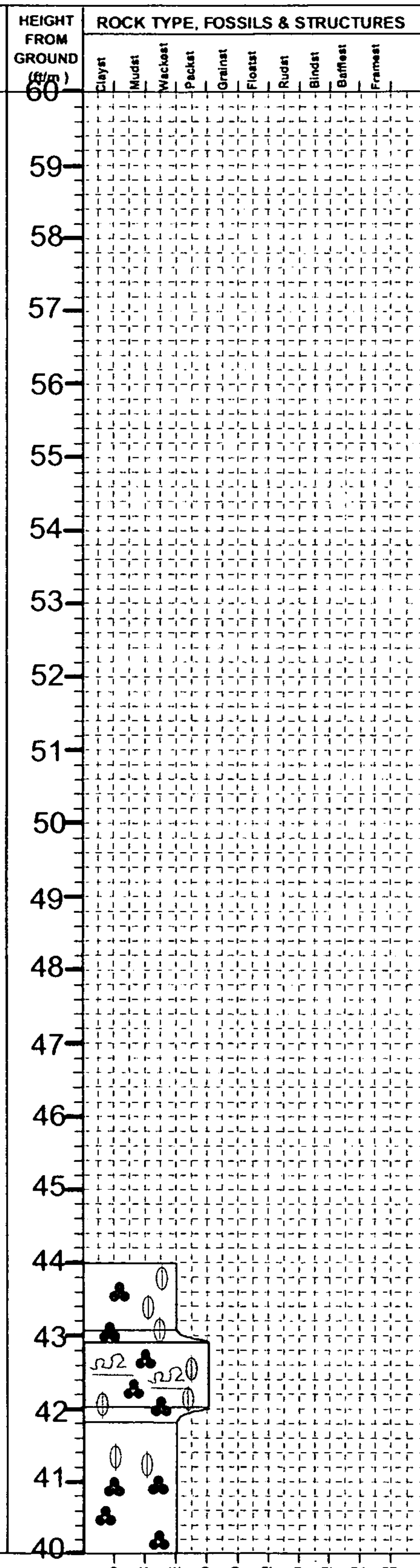
Grey and fined limestone,contains different types of foraminifera (undifferentiated), mollusks (bivalve)

Grey limestone, contain encrusting algae, dense with *Lepidocyclina* spp, various type of fossil (unidentified & identified). The fossil distributed randomly

OUTCROP LOGGING SHEET (Carbonates)

LOCATION/GPS READING: Locality 2 GEOLOGIST:________ DATE: 27/08/2007 SHEET NO. :___ of __

FORMATION NAME	SECTION NO	HEIGHT FROM GROUND (ft/m)	ROCK TYPE, FOSSILS & STRUCTURES	LITHOLOGY	DESCRIPTIVE NOTES
Locality 2 Melinau Formation					



Grey and fined limestone; contains different types of foraminifera (undifferentiated), mollusks, other types of fossil

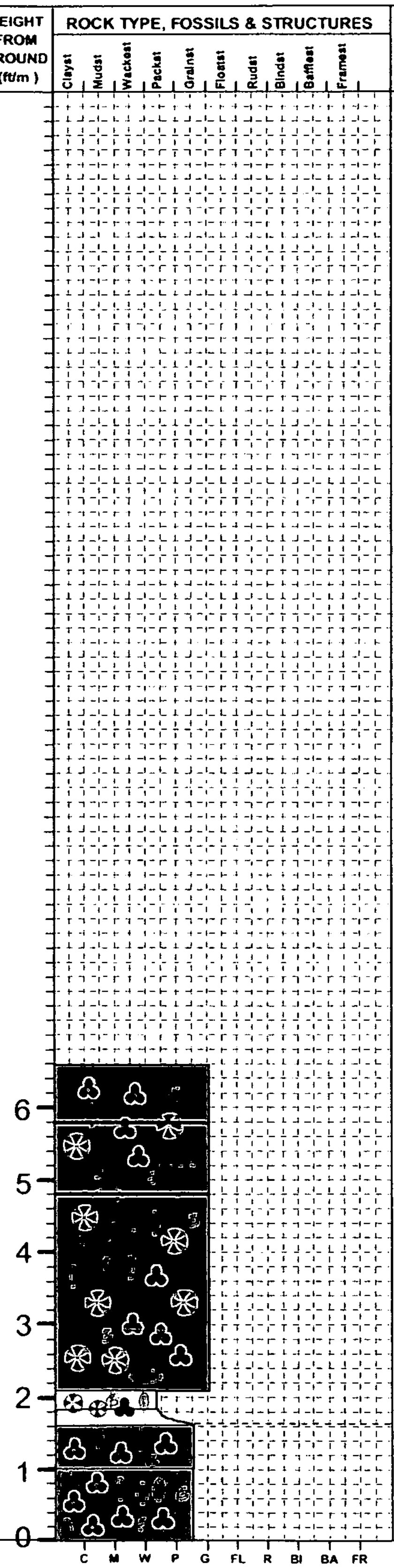
Grey limestone; contains encrusting algae in various size, *Lepidocyclina* spp.,undifferentiated foraminifera, mollusks and other types of fossils

Grey and fined limestone,contains different types of foraminifera (undifferentiated), mollusks (bivalve) and other types of fossils

OUTCROP LOGGING SHEET (Carbonates)

LOCATION/GPS READING: Locality 3 GEOLOGIST:________ DATE:24/08/2007 SHEET NO. :___ of __

FORMATION NAME	SECTION NO.	HEIGHT FROM GROUND (ft/m)	ROCK TYPE, FOSSILS & STRUCTURES	LITHOLOGY	DESCRIPTIVE NOTES
Melinau Formation					
Locality 3					The breccia limestone part, grey in color, the angular size of grains is from 2 cm. The grains deposited without any arrangements, randomly distributed. Contains mollusks (bivalve), fragmental fossil, foraminifera (identified & unidentified), corals (branching and massive). Some calcite veins on the limestone surface
					contact surface
					Grey-dark color limestone, more muddy, contains a lot of foraminifera (identified & undifferentiated), *Lepidocyclina* spp.? No arrangement of fossil. Some calcite veins on the limestone surface. At the upper part is less muddy compare to the bottom part. Very fined limestone.
					More muddy limestone



APPENDIX B

Plate 1.1: The part of larger foraminifera; *Nummulites* sp. The internal body has been cemented by fibrous calcite. Picture taken from sample S1-9, plane polarized light

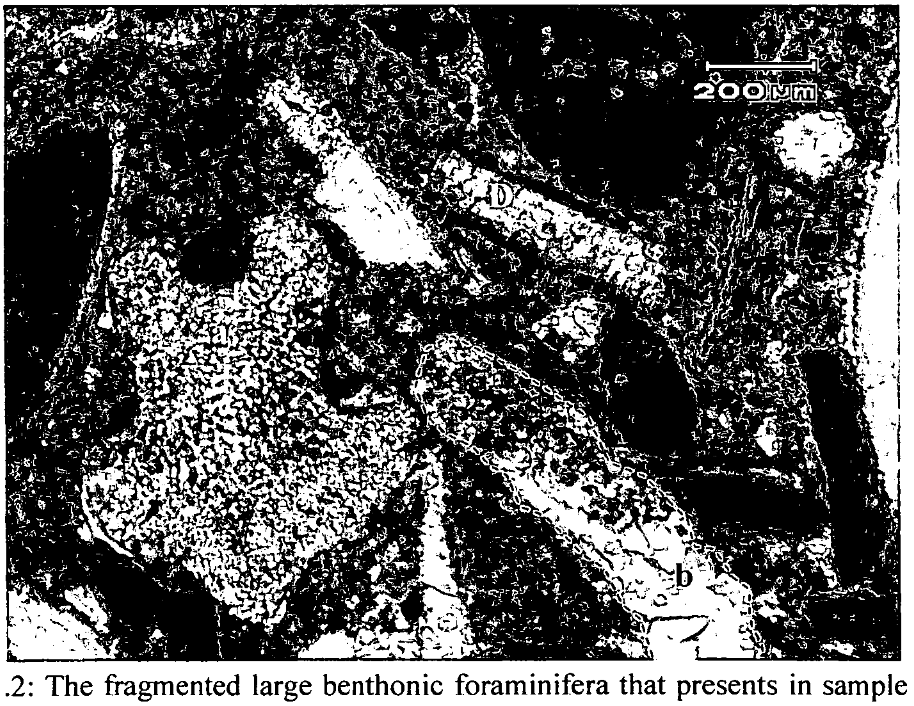


Plate 1.2: The fragmented large benthonic foraminifera that presents in sample S2-9, *Discocyclina* spp.? (D) and unidentified foraminifera (a). The algae skeletal (----, b) has been dissolved and later cemented by iron rich calcite (blue color). Plane polarized light

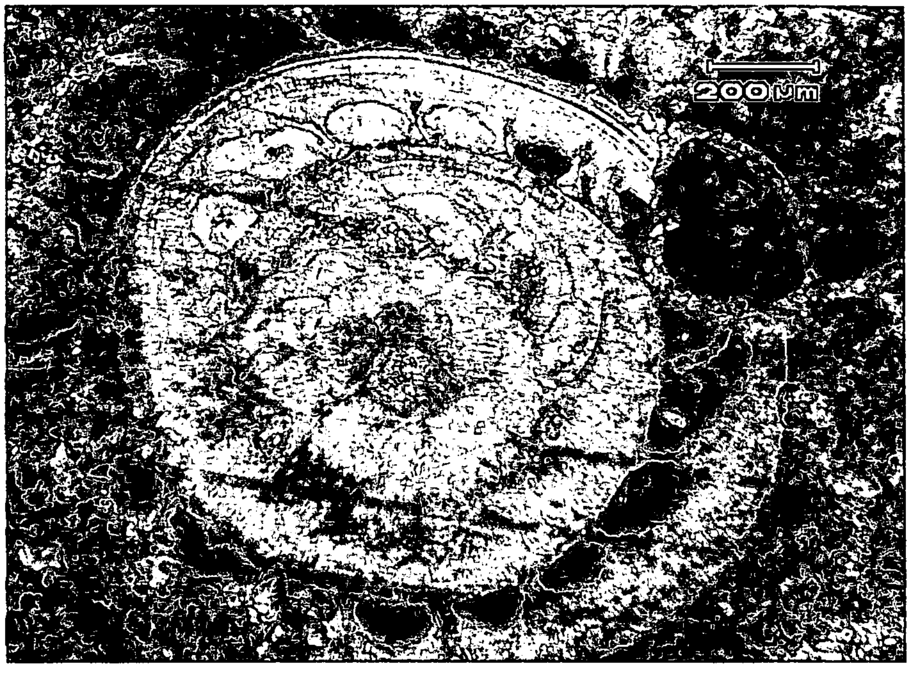


Plate 1.3: The large benthonic foraminifera *Operculina* spp., axial section in sample S1-6. Plane polarized light

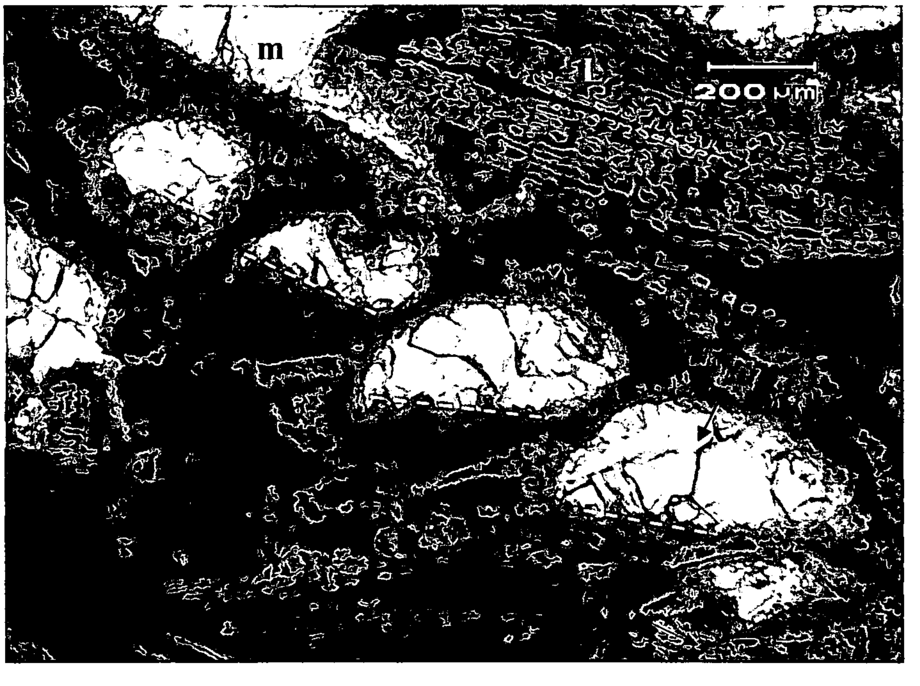


Plate 1.4: An example of geopetal infilling (----) in the remaining cavity of large benthonic foraminifera that filled up by fibrous and equant calcite (arrows). The micrite (m) have been cemented by the same calcite. The example of *Lepidocyclina* spp. shows as (L). Sample taken from S3-6, plan polarized light

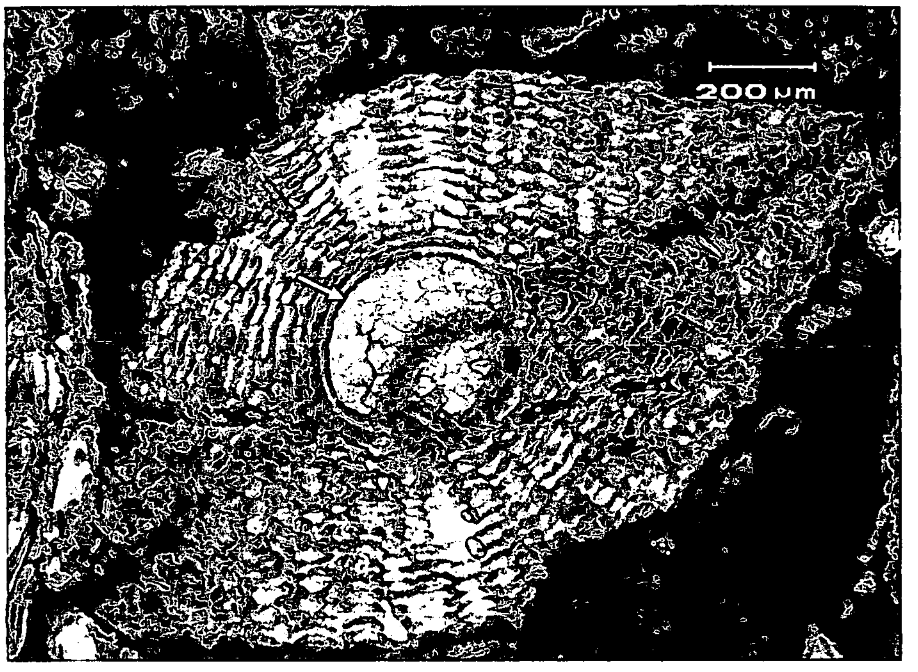


Plate 1.5: An example of *Lepidocyclina* spp. represents from sample S1-7 shows the cementation at the middle part of internal skeletal. The cementation changed from fibrous to equant through the middle (arrow). Plane polarized light

Plate 1.6: The compacted benthonic foraminifera presents in the sample S2-7. The identified fossils are *Operculina* spp. (a: axial section, b: transverse section), *Lepidocyclina* spp.? (l) and undifferentiated foraminifera surround. Plane polarized light

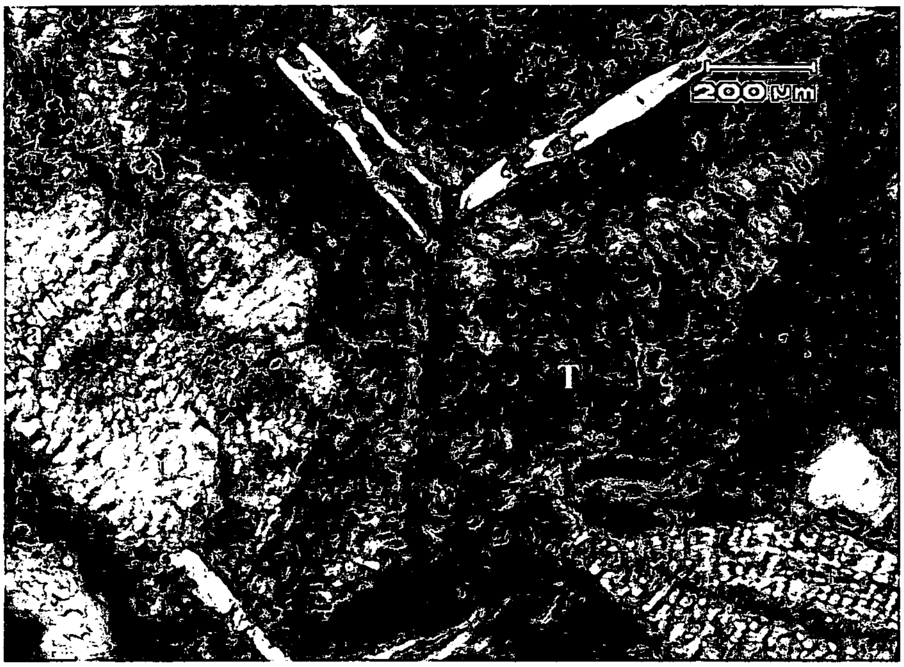


Plate 1.7: Sample from S2-8 demonstrates the larger benthic foraminifera (unidentified; a), *Lepidocyclina* spp. (L), and the rare presence of *Textularia* spp. (T).The micritization replaced the internal part of *Textularia*. Plane polarized light

Plate 1.8: The abundant presences of benthonic foraminifera and echinoderm spine that floating in the micrite. Sample S3-8, plane polarized light

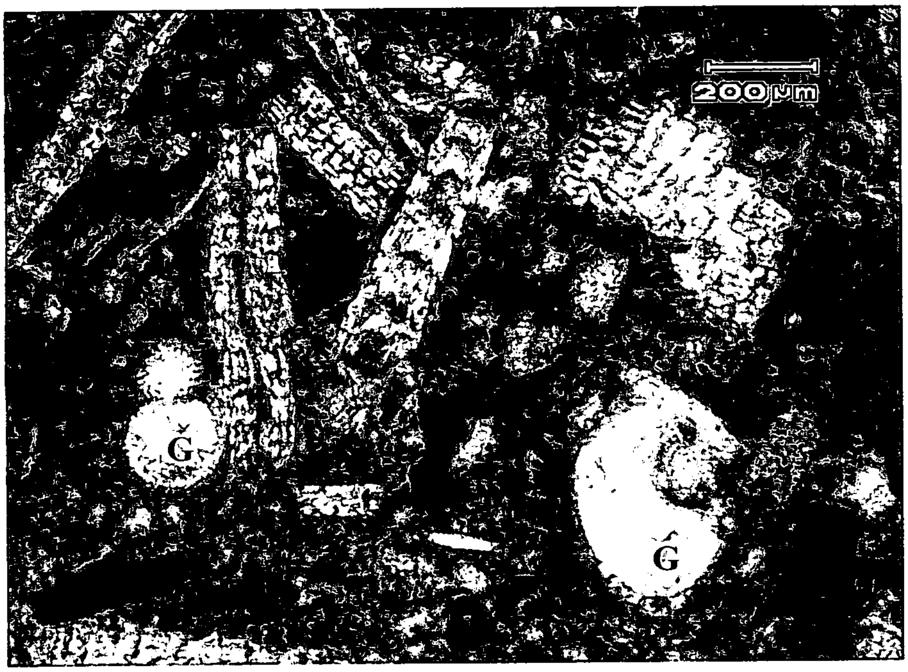


Plate 1.9: The large benthic and plancktonics foraminifera that found in the sample S1-2. The sample shows the foraminifera were fragmented and *Globigerina* spp. (G) has been cemented in the inner part. Plane polarized light

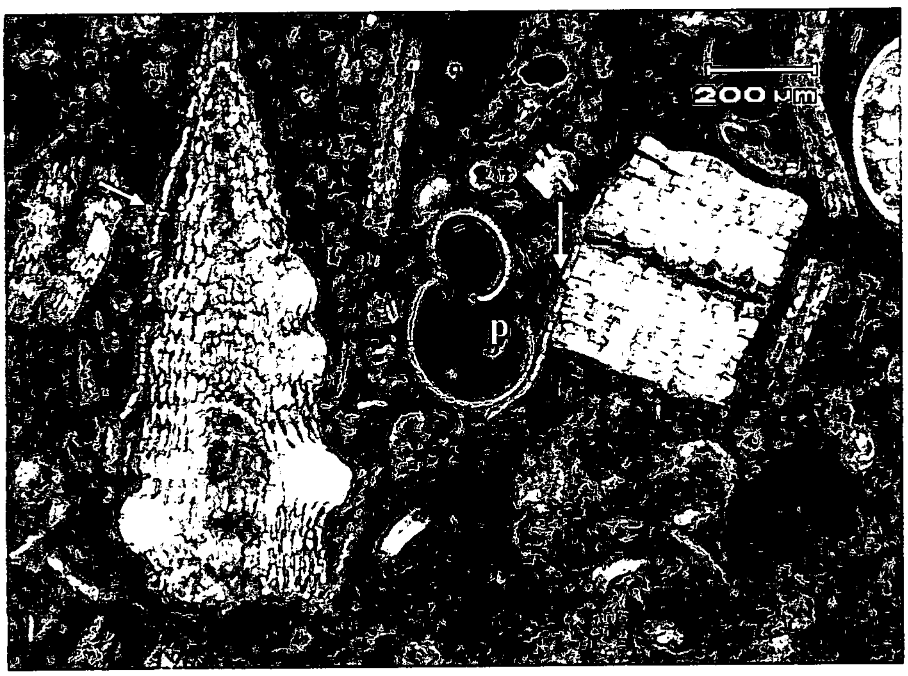


Plate 2.0: The sample from S2-2 that shows the fragmented benthonic and plancktonic (p) foraminifera. The calcite vein (arrow) cut through the foraminifera skeletal. Plane polarized light

Plate 2.1: The highly calcite cemented occurred in the fossils skeletal. The process started with the dissolution of the inner part and then the cementation. The cement develops as fibrous cement (arrow) and become wider at the middle (equant). Also, the compaction (----) is occurred within the calcite. The (f) shows the large benthonic foraminifera (unidentified). Plane polarized light.